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THE RELATIONSHIP OF GEOPHYSICS TO GEOLOGY*

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In this paper, the term "geology" should be interpreted to mean petroleum geology; and the term "geophysics," to mean the use of physical methods and observations to assist the geologist in the location of oil and gas deposits.

Ever since the initiation and application of the structural theory, geologists have been attempting to map the attitude of sedimentary beds. Their early work in the United States was essentially surface structural mapping, which reached its peak during the period between 1915 and 1920. Following this period, more attention was given to subsurface structural mapping based upon a close study of wells which had been drilled in the areas of interest. The samples derived from the wells were carefully studied, better logs were obtained, and it was found in many areas that paleontological markers existed which could be used for structural mapping. In other areas, a study of the samples revealed marked differences in lithological character between formations. In some areas, structural mapping at a shallow depth could be accomplished by the core drill. However, geologists needed still more knowledge of the structural conditions in areas of promise than purely geological methods would provide.

This need of better methods for mapping structures or finding structural anomalies proved to be the "mother of geophysical invention." The aid of physicists was enlisted and they constructed instruments with which to measure the various physical properties of the earth's crust.

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Two of these instruments which were used at an early date are the torsion balance and the refraction seismograph. These were most successfully used in the Gulf Coast where oil accumulation was associated with salt masses easily distinguished from the surrounding sediments. The distinctive feature in the case of the seismograph was the travel-time differential of elastic waves between the salt mass and the surrounding sediments. The distinctive feature in the case of the torsion balance was the difference in density between the salt mass, cap rock, and the surrounding sediments.

The magnetometer was widely used in an attempt to correlate magnetic variations with structural conditions.

Numerous electrical methods were employed in attempts to locate faults, oil—water boundaries, and shallow structures by measurements influenced by the electrical characteristics of the sedimentary layers and their associated fluids.

Radio-activity measurements, thermal measurements, and chemical analysis of soil and soil gas have also been tried.

The reflection seismograph, using elastic waves reflected at acoustic discontinuities associated with the sedimentary beds, has been used to map many types of oil-bearing structures.

The gravimeter, the operation of which depends upon the same density difference utilized by the torsion balance, has also been used.

While the use of these tools by the physicist, working with the geologist, has increased the oil reserves and wealth of the nation by many billion dollars in the past few years, some geophysicists express doubt that the process can continue long unless new and radically different methods are developed. Recently some geologists have minimized the importance of structural accumulation in the present and future search for new reserves, pointing out that some of the largest fields in the United States have been stratigraphic traps.

The idea of the so-called stratigraphic traps, wherein structure was considered a relatively unimportant factor, was advanced at a time when new structural information was slow in materializing. East Texas, Glen Pool and Burbank are pointed out as examples of this type of accumulation. East Texas, probably the outstanding field of this class, was considered to be a shore line or strand line sand body falling in the category of a stratigraphic trap. Later analysis of subsurface data has shown that, while it may be classified as a stratigraphic trap, still it is closely related to the structural growth of the area. The east side of the East Texas field does not mark the farthest

east limit of Woodbine deposition. The Woodbine sand of East Texas is clearly a truncated sand, overlapped by the Austin Chalk, the reason for the truncation being early structural upwarp in the Sabine area. In the light of more complete information, it appears probable that few purely stratigraphic traps, without structural influence, occur. Although fields of this type might be difficult to discover by geophysical methods, nevertheless, after development is begun, structural information of great value to the geologist can be supplied by present geophysical methods. Complete structural information in East Texas shortly after the original discovery would have saved many thousands of dollars spent in drilling dry holes, and in buying unproductive leases.

It appears, then, that even in the case of the relatively rare stratigraphic accumulations, present geophysical methods are of definite value. However, the most important accumulations of oil and gas discovered in the past have been those of some definite structural type. There are good geological reasons for believing that this will continue to be true in the future.

Many areas present definite possibilities for structural types of accumulation, and, because of insufficient exploration in the past or because of the realization of the presence of new types of structures they are promising areas for geophysical exploration by well-known methods.

For example, in the Gulf Coast of Texas and Louisiana, the principal search in the past has been for structures with considerable closure, that is, of the order of several hundred feet. It is probable that most of these large features have been discovered.

Many of the recent discoveries have been of a different type, as, for example, Fairbanks, Eureka, Clinton, South Houston, and League City in Texas, and Tepetate in Louisiana. All of these fields are associated with faulting, and none of them exhibits any surface evidence of faulting. It is highly probable that many such fields will be found in the future.

A second type of field, now becoming important, is represented by such discoveries as Ace in Polk County, Texas, and Ville Platte and Eola in Louisiana. These fields are accumulations of oil and gas on structures showing relief in the neighborhood of one hundred feet. Many structural anomalies of this type should be present in the Gulf Coast areas.

Somewhat similar situations exist in many other areas, making

them highly desirable prospects for structural exploration by present geophysical methods. Among the regions which offer promise are:

(1) The Gulf Coast areas of Texas, Louisiana, and Mississippi, where many deep-seated salt structures are certain to exist and where there are many low-relief structures yet unmapped and numbers of faults whose delineation, throw, and hade are unknown.

(2) The interior embayment of these three states.

(3) West Texas and New Mexico, where structural information at great depths might lead to the discovery of new Ordovician fields.

(4) California, where low-relief structures are suspected of being present.

(5) Illinois, Indiana, and Kentucky. These states are partly covered by a mantle of glacial drift and alluvium.

(6) Michigan, which also is covered in many places by thick glacial drift.

(7) The basins of Wyoming and Montana, where, for the most part, rocks of Cretaceous age are concealed by younger Tertiary, non-marine and continental deposits.

(8) Southern Oklahoma and North-central Texas, where beds of Permian age obscure the structure of older Pennsylvanian and Paleozoic rocks.

(9) Western Oklahoma and Western Kansas, where Permian and Cretaceous beds obscure the structure of the older Paleozoic rocks.

(10) Many other virgin but promising areas for exploration, such as Northeastern Mississippi and Northwestern New Mexico.

Until the detailed structural information in each and every one of these highly promising, potentially oil-producing areas is fully known, there yet remains plenty of structural mapping to be done. With this picture in mind, present geophysical methods should be examined.

Possibly the best criterion of a successful exploration method is that it should show a positive anomaly where structure exists, and should show a non-structural area as negative. The ability to localize anomalies closely and determine depths accurately is also very desirable.

The refraction seismograph was peculiarly adapted to the Gulf Coast problem and gave an excellent account of itself there. With the improved equipment of today, the refraction seismograph can probably still be successfully used in some areas. However, many factors should be taken into consideration before adopting the use of refraction seismograph in a given area. The size and amount of uplift

to be expected over structures is important, as is also the velocity variation of the section on and off the anomaly. Anomalies cannot be localized closely when long refraction shots are used. This necessitates a follow-up by other methods.

The torsion balance also found an ideal situation in the Gulf Coast. In this region, it has many oil-bearing structures to its credit. However, it often shows an anomaly where none exists in the sedimentary beds. In most areas, very detailed and extensive work must be done to extract regional variations from the results in order to be sure that any anomaly found is not entirely associated with the basement complex. The torsion balance has some difficulty in localizing anomalies closely, and a survey by other methods is required to complete the work.

The chief weakness of the magnetometer is that it does not show a non-structural area as negative. Its chief value would seem to be in general problems such as the tracing of granite ridges. Even here it is necessary to check by another method before much reliance can be placed in the results.

The electrical methods, although they have been in limited use for several years, are apparently still in the experimental stage. Some interesting results have been obtained on carefully selected problems; but, in general, their usefulness is quite limited. The depth to which these methods work dependably is too small to allow general application of electrical methods. Simple geologic sections seem to be necessary for satisfactory interpretation.

Radio-activity measurements, thermal measurements, and chemical analysis of soil and soil gas are of undemonstrated value.

The gravimeter has much the same limitations as the torsion balance, but, because of faster operation, lower cost, and greater freedom from nearby surface effects, it appears much more attractive as a reconnaissance instrument than the torsion balance.

The reflection seismograph has a brilliant record of performance and is free from many of the faults of other methods. No other method compares with it in ability to find structure and to detail it. It is the only method which will give accurate depths to definite beds. It has no serious depth limitations. It comes closer than any other geophysical method to showing regularity where there is very little likelihood of structure existing. While there are limited areas where results are poor, there are no vast areas where satisfactory results cannot be obtained. In many areas, it is the only method which has

been successful in locating structural conditions favorable for the accumulation of oil and gas. In the Gulf Coast, the number of structures located by the reflection seismograph is equal to or exceeds the number found by all other methods combined. In many areas where the reflection seismograph followed intensive work by all other methods, it has been able to locate a large number of structures, passed up by the other methods.

Therefore it is probable that, in the final analysis, the use of other methods will have to be followed by such widespread use of the reflection method that to have done the work originally with the reflection seismograph would have been cheaper in both dollars and time.

The intensive research and development which have produced such outstanding improvements as diversity recording and dependable, distortionless, automatic control of amplification will undoubtedly continue to produce improvements that will maintain the reflection seismograph in its present superiority over other methods.

A geological study of the yet unworked areas of the United States shows that most of them can be economically and profitably worked by the reflection seismograph. Considering the possibilities of all present methods, and realizing that the development and general acceptance of a radically new method will require several years, it seems safe to predict that for the location and development of oil and gas structures during the next few years the geologist will depend upon the reflection seismograph to at least as great an extent as in the past. The other methods, particularly the gravimetric methods, will, of course, have their place. Although the last word will, in all cases, be the actual drilling of structural anomalies, prior to that development the most complete and reliable information will be given by the reflection seismograph.

ON THE STRATEGY AND TACTICS OF EXPLORATION FOR PETROLEUM, III*

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INTRODUCTION

In the preceding paper[1] of this series, it was pointed out that three of the Principles of War, those relating to the Offensive, Surprise, and Security, were applicable to Exploration for Petroleum. The following discussion examines the similar applicability of two other Principles of War, the first, that relating to the Objective, and the fourth, that relating to Economy of Force. These are as follows.

A. THE PRINCIPLE OF THE OBJECTIVE (1)

"The purpose of a military operation is the attainment of the objective assigned a given force. This objective constitutes the guide for the interpretation of orders, for the formulation of decisions, and for the employment of the means available. The nation, its military forces, and each element of the latter have their objective."

THE FIRST PRINCIPLE OF WAR[2]

With regard to the applicability of this principle to Exploration for Petroluem, it need simply be pointed out that, contrary to a rather generally held assumption, the discovery of oil is a necessary but not a sufficient condition for a successful exploration campaign. Those discovery wells in Western Kansas which have been shut in for a year because of lack of outlet; those other discoveries of oil which were made about the time that East Texas broke the price of crude oil; and the practice of farming out the drilling of proven locations in the Permian Basin; all these phenomena testify to the fundamental nature of the Principle of the Objective, i.e., that the Objective of Exploration is the discovery of oil under the most favorable conditions of *time*, *place*, and *investment*.

* Read at the Annual Meeting, Oklahoma City, Oklahoma, March 21, 1939.

† Subterrex.

[1] On the Strategy and Tactics of Exploration for Petroleum, II, GEOPHYSICS, Vol. 3, No. 1, Jan. 1938, pp. 22–39.

[2] W. A. Mitchell. *World's Military History*, p. 737. Military Service Publishing Company, 1931.

B. THE PRINCIPLE OF ECONOMY OF FORCE

"The application of the Principle of Economy of Force is the means by which the mass to be employed in a main effort is to be obtained (utilized). The time and place of the main effort having been determined, men and means are conserved by reducing their employment in other directions to the minimum consistent with safety."

THE FOURTH PRINCIPLE OF WAR[3]

INTRODUCTION

To a large extent, this principle refers to the choice and optimum sequence of tactics. In the first[4] of this series, the choice and sequence of tactics were discussed, and the conclusions drawn that:

"1. Prospects should first be located by the appropriate method of lowest operating cost. These prospects should be evaluated and culled by the successive use of the appropriate methods of higher cost (Successive high-grading).

2. Prospect development in a particular area should not be initiated by any given method until the area has been primarily explored by the appropriate methods of lower cost."

In this earlier discussion of the choice and sequence of tactics, primary consideration was given to the operating costs of prospecting methods, while the relative functions of the different methods were generalized by reference to the "appropriateness" of the methods themselves.

Further consideration of the general properties of exploration methods indicates that the "cost" criterion was, and remains, correct. However, to further elucidate that point, and also to furnish better criteria than "appropriateness," the following discussion is submitted, wherein the general properties of the various exploration methods are better described.

The Two Major Classes of Exploration Methods

Exploration methods fall into two major general classifications; first, the *structural prospecting methods*, which result in three dimensional maps, and indicate the presence of favorable structure through vertical changes in sedimentation, (i.e., by the determination of depths and differential depths); and second, the *stratigraphic pros-*

[3] W. A. Mitchell. *loc. cit.*

[4] On the Strategy and Tactics of Exploration for Petroleum. E. E. Rosaire, *Journal Society Petroleum Geophysicists*, Vol. VI, No. 1, 1935, p. 19.

pecting methods, which result in two dimensional maps, and indicate the presence of favorable structure through lateral changes in sedimentation. As illustrations of the former, the drill and the reflection seismograph are typical, and as illustrations of stratigraphic prospecting methods, the magnetometer, the torsion balance, and refraction-fan exploration have been the most widely used. The general characteristics of these two classes of prospecting methods are discussed in the following paragraphs.

The Structural Prospecting Methods, Their Properties and Limitations

Structural prospecting methods can be divided into two classes, the *pseudo* structural prospecting methods, and the *true* structural prospecting methods. In the first class are depth determinations by stratigraphic prospecting methods, i.e., profiles by refractions, and by electrical, gravity, and magnetic methods. In the latter class are depth determinations by the *true* prospecting methods, the reflection seismograph and the drill.

The utility of any structural prospecting method is dependent upon the cost, the penetration, and the observational error of the resulting depth determination.

Pseudo Structural Prospecting Methods

These methods yield depth calculations from a succession, in close profile, of stratigraphic determinations, and include profiling by refraction, electrical, gravity, magnetic and geo-chemical methods. Since the profiling is slow and requires an appreciable surface coverage, the pseudo structural depth determination tends to be unwieldy, slow, costly, of relatively low penetration, and involving assumptions as to the lateral homogeneity of the penetrated sediments, is often associated with high observational errors.

The usefulness of these pseudo structural prospecting methods tends to be specific rather than general. Thus refraction profiling is most useful in the determination of very shallow depths, and for approximate depth determinations to an interface of relatively large seismic velocity changes, not readily or obviously indicated by reflections (as in the depth to the unweathered layer, or the depth to the granite basement). Electrical profiling is widely used in the location of, and the depth to, shallow aquifers, and gravity depth determina-

tions have played a useful part in detailing the depth and size of cap rock over shallow salt domes.

Except for such specific cases, it is difficult to see the justification for the general use of such pseudo structural prospecting methods, for as we probe deeper for structures of lower and lower relief, their characteristically limited depths of penetration, and their high observational errors, render these pseudo structural prospecting methods less and less generally useful.

True Structural Prospecting Methods

In this class are the reflection seismograph and the drill, both of which are characterized by attainable depths of penetration quite satisfactory for our present prospecting, and with observational errors generally less than those characteristic of the pseudo structural prospecting methods. For the drill, the attainable depth of penetration is about 15000 feet at the present time, and, conceivably, could be pushed below that point. For the reflection seismograph, the depth of penetration is apparently even greater, reflections having been reported from estimated depths of 30,000 feet or more in the Gulf Coast. The observational errors of depth determinations by the drill have been reduced materially through the aid of the core barrel, micro paleontology, electrical logging, and the drill stem tester. The observational errors for the reflection seismograph have been reduced materially, largely by the use of velocity determinations from drilled wells. However, cases of large observational errors from reflection depth determinations not infrequently occur in prediction of the depth to the basement, and in the case of faults of material throw.

However, the limitations of the true structural prospecting methods are more practical than theoretical. Thus, not all wells are drilled to the maximum depth attainable with the existent drilling technique, leading to the type of failures such as the Belvidere Oil Company's dry hole, which, if drilled 181 feet deeper, would have discovered the Sugarland oil field (in 1922); or the Roxana's #1 Mayes Estate, which would have discovered the Lost Lake salt dome if drilled 500 feet deeper in October 1925; or, again, in the Oklahoma City Field, where "as early as 1925 L. R. Trout drilled a well in Section 36, T 11N., R. 3W to a depth of 4,480 feet and encountered in this test, before abandoning it, several small showings of both oil and gas, stopping 2,000 feet above the Wilcox sand, where, on exactly the same location, Sinclair-Prairie Oil Company later completed its

School Land 67 No. 5 for 20,000 bbl. per day."[5] Another similar misuse of a structural prospecting method was the recent practice in California of tearing off reflection records at 5 or 6 seconds in the early exploration there by that method, necessitating a complete re-exploration of that area later when deeper information became advisable and necessary. Such practices should be charged against the misuse of the methods rather than against the methods themselves. But the extent to which such failures occur illustrates a practical limitation on structural prospecting methods, in that the question frequently remains, was the actual penetration great enough?

Another limitation on one important structural prospecting method, the reflection seismograph, is inherent in its use, i.e., the extent to which production is associated with structure. That is, if the producing zone is not associated with a closed structure, or if the producing zone is absent, or grows more favorable (more porous), away from the apex of the structure, accurate depth determinations by the reflection seismograph are no longer sufficient in themselves.

The Stratigraphic Prospecting Methods

The stratigraphic prospecting methods yield two dimensional maps, and depend upon the measurement of some general property of the earth at some point or localized area on the earth's surface. To date there have been recognized five such types of measurements, magnetic, electrical, acoustical, gravitational, and chemical. As was mentioned previously, a profile of any such stratigraphic measurements takes on some of the characteristics of a depth determination, (pseudo structural methods), which, except for specific purposes, rarely has the merit of a depth determination by a true structural prospecting method.

However, the more general field of usefulness for the stratigraphic prospecting methods is, and has been, in reconnaissance; in the recognition of the presence and approximate areal extent of favorable structure. In that classification of true stratigraphic prospecting fall the campaigns based upon areal coverage by the magnetometer, the torsion balance (generally superseded now by the gravity meter) and refraction "fans." The significant anomalies discovered on such campaigns were displayed on two dimensional maps, yielding indications of the presence and approximate areal extent of favorable structure.

[5] "Geology and Economic Significance of the Oklahoma City Field," Basil B. Zaroico, *World Petroleum*, Jan. 1935, p. 11.

The fundamental limitations of these stratigraphic prospecting methods are the absence of any indication as to the depth or associated relief of the favorable structures so indicated.

Thus, during the Gulf Coast refraction campaign, it was generally assumed that the significant anomalies observed were primarily due to the uplift of the deeper, older, beds which were generally characterized by higher seismic speeds. That hypothesis was generally accepted, and so the method became obsolete, not because of the failure to observe anomalies greater in magnitude than the associated observational errors, but because the last tested anomalies did not prove to be the uplifts expected, i.e., piercement type salt domes. As a matter of interest, there remain in the Gulf Coast two refraction anomalies characterized by "leads" typical of shallow salt domes, (i.e., 0.4+ seconds) which are not definitely associated with closed structure discernible by the reflection seismograph.

Similarly, torsion balance exploration passed into near obsolescence for a similar reason, for many gravitational minima are recognized in the Gulf Coast today which are, apparently, not associated with closed structure discernible by the reflection seismograph.

It can probably be said that the number of remaining unproven, or the apparently disproven, gravitational and refraction anomalies outnumber the anomalies found by these methods which have proved to be associated with closed structure. Statistically, then, those two techniques have been of questionable value; actually, however, their confirmed predictions have, without question, led to the discovery of many economically significant oil fields.

In retrospect, then, it can be said that these two prospecting techniques, recognized as of major significance, have found "too many" anomalies, a charge which has a familiar ring. I heard that same objection raised in the early Gulf Coast reflection exploration, and have heard it made again with reference to the new exploration techniques which are now being introduced. Two factors contribute to the presence of "too many" stratigraphic evidences of favorable structure, the first of which is that the number of favorable structures tends to increase as the associated relief decreases,[6] and second, that these stratigraphic evidences of favorable structure tend to occur without regard to the depth or the relief of the indicated structures.

[6] The Paradox of Exploration. E. E. Rosaire. *World Petroleum*, Oct. 1938, pp. 38–42.

ESTIMATING DISCOVERY COSTS

The Cost of Discovery

An exploration campaign is based upon the consideration of widely extended *possibly* productive areas, and the selection and subsequent drilling of localized *potentially* productive areas. The ultimate evaluation of the merit of such a campaign will be determined by the actually observed discovery costs as contrasted with contemporary and equivalent discovery costs for the industry.

However, for proper budgeting of such a campaign, it is advisable to have some rational method of estimating the costs for the average discovery. Such method of estimating should be sufficiently general to be adaptable not only to different areas, but also to different exploration tactics, so as to permit a reasonable comparison of the relative utility of different exploration techniques. Finally, and most important, such a method should yield estimated discovery costs of the same order of magnitude as those actually observed under the conditions contemplated.

The cost of discovery includes, properly, first the cost of finding, or the reconnaissance cost required to recognize one favorable area; second, the cost of securing leasehold, and finally, the cost of the actual discovery, which includes the cost of selecting the most favorable drill site, and the cost of the test well.

In an orderly campaign, then, the cost of finding one favorable area will include the "not finding" cost of examining the other areas which are of no economic significance. Obviously, the cost of finding is made up, primarily, of the cost of "not finding," or the cost of exploration over unfavorable areas.

An estimate of the finding cost, to be expected for one discovery, can be made in the following manner, from which, for simplicity, the cost of leasing has been omitted. To estimate the cost of discovery, the following points must be given consideration. First, the percentage which, it can reasonably be supposed, the ultimately productive acreage will bear to the total possibly productive acreage, for that ratio indicates the total number of unit areas which must be considered in the selection of one discovery of average areal extent. Second, an estimate of the number of individual determinations which must there be made by the exploration technique, used in this selection, to recognize a *potentially productive area* as differentiated from one of *no economic importance.* Third, an estimate must be made of

the cost of each such determination by that particular method of exploration. With these three factors, an estimate can be made of the finding cost to be expected of any given exploration technique.

To carry the estimate through to a logical conclusion, however, the costs of securing leasehold, and the cost of the actual discovery, should also be considered. However, a discussion of lease tactics is outside the scope of this paper, and so, for simplicity, that factor is omitted. However, the costs of actual discovery can be reasonably estimated, and include the cost of selection of the drill site as well as the cost of the discovery well.

For purposes of illustration, let us consider an exploration campaign to be launched in the Gulf Coast, where Duessen[7] has estimated that one percent of the possibly productive area will ultimately produce oil. That is, for one hundred areas considered there on the average, only one will produce, although the cost of examination of the ninety-nine non-productive areas must be charged against the one productive area so found.

In Table I, such estimates of discovery costs have been made up on, first, the cost of finding one favorable area (the reconnaissance costs), and second, the costs of actual discovery.

Since the test well is a necessary adjunct of discovery, frequent consideration has been given to, in fact exploration campaigns have been predicated upon, the use of the drill alone. Estimates of the discovery costs to be expected from such a campaign have been indicated in the first column, while a similar estimate has been made in the second column for an exploration campaign initiated by another structural prospecting method, the reflection seismograph. In the third column is an estimate for discovery costs to be expected from a campaign initiated by one stratigraphic prospecting method, the Electrical Transient method, while in the fourth column, an estimate is made for an exploration campaign introduced by the simultaneous but independent use of two stratigraphic prospecting methods, the Electrical Transient method and the gravity meter.

As was said above, the method used for estimating discovery costs must not only be applicable to different exploration tactics, but the resulting estimated costs must also be of the right order of magnitude. The method proposed above has been sufficiently general to be adaptable to varied exploration tactics, and as to the correctness of

[7] Discoveries. A. Duessen, GEOPHYSICS, Vol. III, No. 3, July 1938, p. 195.

TABLE 1

ESTIMATED DISCOVERY COSTS
To be Expected from an Orderly Exploration Campaign Initiated by

	A Structural Prospecting Methods (Three Dimensional Maps)		B Stratigraphic Prospecting Methods (Two Dimensional Maps)	
	1	2	1	2
1. Reconnaisance, by	Drill	Reflection Seismograph	Eltran	Eltran Plus Gravity Meter
A. Cost of one determination	$ 30,000.00	$ 50.00	$ 5.00	$ 10.00
B. Number of determinations required for evaluation of average productive area	1	50	50	50
C. Cost of evaluating one such area	$ 30,000.00	$ 2,500.00	$ 250.00	$ 500.00
D. Number such required for one discovery (1% ultimately productive)	100	100	100	100
E. Finding costs	$3,000,000.00	$250,000.00	$25,000.00	$ 50,000.00
2. Detail, as follows				
A. Eltran			$ 5,000.00	$ 5,000.00
B. Soil analysis			$ 5,000.00	$ 5,000.00
C. Reflection		$ 10,000.00	$10,000.00	$ 10,000.00
D. Test well	(See 1A above)	$ 30,000.00	$30,000.00	$ 30,000.00
E. Detail costs		$ 40,000.00	$50,000.00	$ 50,000.00
3. Discovery costs (1E plus 2E above)	$3,000,000.00	$290,000.00	$75,000.00	$100,000.00
4. Not finding cost (99% of 1E, above)	$2,970,000.00	$247,500.00	$24,750.00	$ 49,500.00
5. Per cent, not finding costs of discovery costs	99%	85.3%	33%	49.5%

the order of magnitude of resulting cost estimate, the following can be said.

The first Gulf Coast exploration campaign, from 1901 to 1923, was based upon the relatively unaided use of the drill, at least in its second stage of diminishing returns and high discovery costs. To that extent it is comparable to A-1 above. Of that campaign, it was estimated[8] that the wildcat drilling, which led to the discovery of the

[8] W. F. Henniger. Geology of Salt Dome Oil Fields, De Golyer *et. al.* A.A.P.G. 1926, p. 776.

last pre-geophysically discovered salt dome, totalled $20,000,000, exclusive of the cost of leasing. That $20,000,000 discovery cost, based on actual performance, is of the same order of magnitude as the $3,000,000 discovery cost estimated in A-1 above, in that they both are far too high.

From 1935 to the present time, the present Gulf Coast exploration has been based, primarily, upon the unaided use of the reflection seismograph, and resulted, from 1935 to 1938, in the discovery of 100 oil fields at an average cost of $140,000 for reflection exploration alone,[9] a figure certainly of the same order of magnitude as the $250,000 estimate, in A-2 above, for a similar campaign.

While no figures are available for checking the estimates for the two campaigns projected, in B-1 and B-2 above, upon reconnaissance by stratigraphic prospecting methods, the following points of interest can be pointed out.

The most spectacular exploration campaign conducted in the Gulf Coast to date was that conducted for the Louisiana Land and Exploration Company by the Geophysical Research Corporation from 1927–1928, when eleven salt domes were found in nine months. That campaign was initiated by a stratigraphic prospecting method, fan exploration by the refraction seismograph. The average finding costs for these eleven domes was less than $50,000 apiece, less than four years after Henniger had estimated a finding cost of $20,000,000 for the last pre-geophysically discovered salt dome, found on an exploration campaign initiated by a structural prospecting method, the drill.

Of recent years, the most outstanding discovery campaign was that conducted by the Stanolind Oil and Gas Company from 1933–1935, when four oil fields were found in one reflection crew year, Hastings, South Houston, Turtle Bay and Clinton. It is interesting to note that these discoveries, generally attributed to the reflection seismograph, actually resulted from the reflection detail of favorable areas found on a reconnaissance campaign with the torsion balance, a stratigraphic prospecting technique.

Another interesting property of stratigraphic prospecting remains to be pointed out. As was illustrated by the torsion balance-reflection campaign staged by the Stanolind, the reflection seismograph, and for that matter the drill or any other structural prospecting method, operates best against a background of prospects. This means that

[9] The Paradox of Exploration, E. E. Rosaire. *World Petroleum*, October, 1938.

when relying solely upon the reflection seismograph, the new comer to an area is at a disadvantage to the local "old timers" who know of old prospects to evaluate, for thereby, they eliminate some of the not finding costs.

Such a background is a big help, for in the case of the structural prospecting methods, the not finding costs are numerically large and comprise about 90% of the ultimate discovery cost for an orderly campaign. For a stratigraphic prospecting method however, such a handicap for the new comer as compared to the old timer is nowhere near as important, for the "not finding" costs are numerically small and comprise only about 33% of the ultimate discovery cost. That is why the Stanolind, a new comer, who relied upon a stratigraphic method (the torsion balance) to spot the structural prospecting method (the reflection seismograph), was able to show, from 1932–1934, discovery costs comparable to those shown by the "old timers," the Humble, The Texas Company, and Pure, during the same period. On the other hand, other new comers who initiated their campaigns with a structural prospecting method (the reflection seismograph), all showed discovery costs much higher than those displayed by the "old timers."

This follows partially from the fact that the "not finding" costs for the stratigraphic methods are so low that interruptions due to frequent moves are unjustified from the standpoint of time saving. That was excellently illustrated in the case of the refraction campaign in South Louisiana, mentioned above. The refraction crews were set up to operate over water, and moves required an appreciable cessation of exploration. Therefore, once a headquarters was established it was found more practical to sweep out all the adjacent acreage (economically coverable), than it was to move these crews from place to place to investigate local areas known to be of possible significance.

Another characteristic of stratigraphic prospecting methods should be pointed out.

Early torsion balance campaigns were "spot" explorations as contrasted with blanket explorations, in that isolated prospects were examined without reference to the surrounding territory. As experience in that technique developed, the torsion balance specialists began to rely upon regional surveys, in fact, found them necessary in order to be able to recognize the minor anomalies which were frequently found to be of economic importance. That conclusion, along with similar conclusions based on equivalent experience with refrac-

tion exploration, indicates that stratigraphic prospecting methods operate to best advantage in regional reconnaissance.

It was pointed out earlier that the significant stratigraphic prospecting anomalies show the presence and approximate areal extent of favorable structure, but yield no direct information as to the depth nor associated relief of the structure so indicated. As illustrations for such a conclusion, attention is called to the Hastings oil field, located on a structure of about 1000 feet of closure at a depth of about 7000 feet, which was first recognized as a submarginal torsion balance minima, less well defined than the similar torsion balance minima at the Eureka oil field, with less than 100 feet of closure at a depth of 7700 feet; or again, the Turtle Bay oil field, with barely 50 feet of closure at a depth of about 6500 feet, which was a better refraction anomaly than the Manvel oil field, with about 600 feet of relief at about the same depth.

CONCLUSION

The method proposed above for estimating discovery costs is sound in that it is applicable to various exploration tactics, and yields estimated costs of the right order of magnitude.

From the estimates made of the discovery costs to be expected from various exploration tactics, as well as from specific and general fact performance, the stratigraphic prospecting methods are obviously better suited for reconnaissance, i.e., for finding and recognizing favorable structure, than are the structural prospecting methods, the drill and the reflection seismograph.

This latter conclusion is particularly true at the present time, since by elimination we are forced into the consideration that our future discoveries must be in the field of low relief structures grading into and including stratigraphic traps, i.e., into conditions wherein structural considerations are less important than stratigraphic considerations. Under such conditions stratigraphic prospecting methods, in that they do not rely upon the depth or the relief of the structure under consideration, will play a part of greater and greater importance in our future prospecting.

Finally, The Principle of Economy of Force is applicable to exploration for petroleum, and, since it is obviously cheaper to explore in two dimensions than in three, dictates that an exploration program should be initiated by a reconnaissance program based upon stratigraphic prospecting methods, and that the prospects so discovered be evaluated in three dimensions by structural prospecting methods; or, in other words, explore in two dimensions, then probe in the third.

A PROBLEM IN SEISMIC DEPTH CALCULATION*

ROLAND F. BEERS[1]

ABSTRACT

In geologic provinces where surface erosion has removed several hundred feet of section the customary method of depth calculation for the reflection seismograph with an empirically determined velocity function frequently fails to show true sub-surface relief. Seismograph structure maps frequently show evidences of the surface topography and intervals between two reflection horizons may appear in excess of the true value. A method is presented here which seems to eliminate the effect of topography on the depth calculations.

During the course of reflection seismograph surveys in areas of great surface erosion, the problem frequently arises of the proper method of calculating depth to reflection horizons. When the customary method of depth determinations is employed with an empirically determined volocity function, it is noted that the resultant structure map bears evidences of the surface topography. Topographic lows are expressed as subsurface highs; ridges and other positive surface features appear synclinal. A method is presented here which seems to permit calculations of reflection horizons which are free from the topographical distortion. The method involves considerable labor which can be reduced by certain chart constructions.

Figure 1 shows schematically the problem under consideration. Here we have a geologic section represented by beds A, B, C, D and E. e_1 represents the elevation above sea level of a point on the surface which has not been eroded. e_2 represents the elevation of a point of maximum erosion. The thickness of section removed by erosion is represented by (e_1-e_2). If a reflection seismic station is chosen at S.P. 1, the depth to reflection horizon E is given by Z_1. At S.P. 2, the depth to the same horizon is given by Z_2. If the horizon E is flat lying between these two stations, then D_1, the sea level datum at 1, equals D_2, the sea level datum at 2. In other words:

$$D_1 = e_1 - Z_1$$

$$D_2 = e_2 - Z_2$$

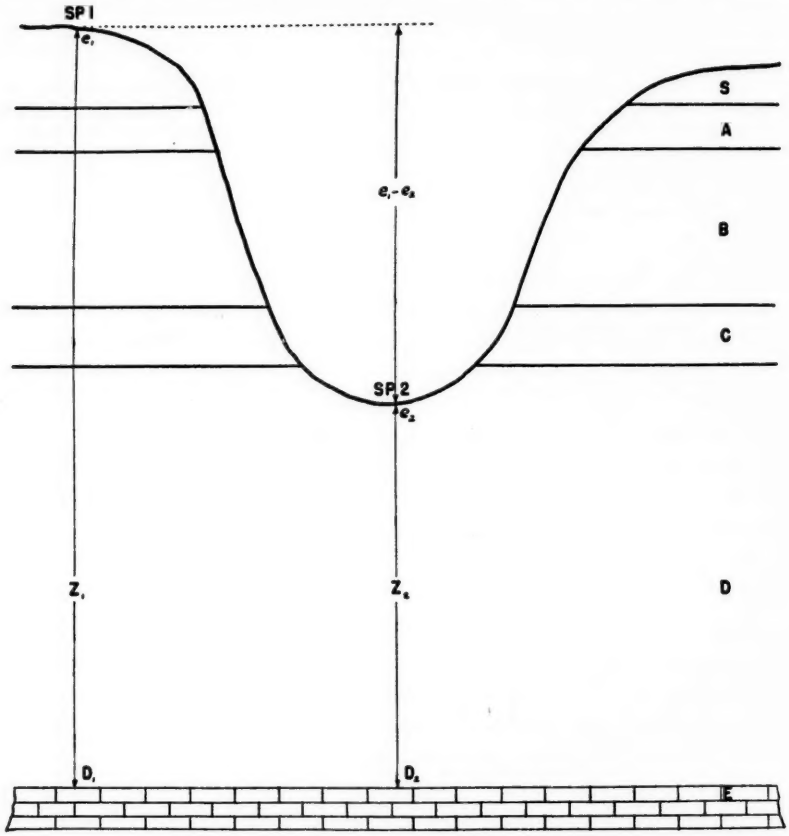
and

$$D_1 = D_2.$$

* Presented at the New Orleans meeting of the S.E.G. in March 1938.

[1] The Geotechnical Corporation, 902 Tower Petroleum Bldg., Dallas, Texas.

In the usual method of calculating D_1 and D_2 an empirically or otherwise determined velocity function is applied to the reflection arrival times at 1 and 2, thereby yielding values for Z_1 and Z_2. Such



$D_1=e_1-Z_1$ $D_1=D_2$ $D_2=e_2-Z_2$

FIG. 1. Schematic diagram of reflection shooting problem with erosional topographic feature.

velocity functions usually have a rate of increase of velocity with depth (the velocity gradient). A simple form of velocity function is given by:

$$V_z = V_0 + KZ \tag{1}$$

feet per second.

By use of formula 1, depths at Z_1 and Z_2 are computed in the ordinary manner. If, for example, a mean spread of X feet between shot point and mean recorder stations is employed, then the customary formula

$$V_{z_1}^2 t_1^2 = X^2 + 4Z_1^2 \tag{2}$$

$$V_{z_2}^2 t_2^2 = X^2 + 4Z_2^2 \tag{3}$$

$$Z_1^2 = (V_{z_1}^2 t_1^2 - X^2)/4 \tag{4}$$

$$Z_2^2 = (V_{z_2}^2 t_2^2 - X^2)/4. \tag{5}$$

Employed in this fashion however, there may be a distortion of the true structural picture introduced by the variations in topography. In some of the provinces of Canada, in western New York and Pennsylvania, and in Wyoming, erosional relief may attain a magnitude of as much as 1,000 feet, and this relief has been found to be reflected in surveys computed by the method outlined above.

The reason for the appearance of these errors can be seen from a review of methods in common practice. Wherever possible the average velocity of vertical travel is determined by lowering a detector into a well, measuring the travel time of sound from a point near the surface to successive positions in the well. The data taken from these observations are of fundamental dimensions, time and distance. From these two quantities it is customary to compute derived quantities, e.g. velocities. A graph is then prepared for convenience in making subsequent calculations; on this graph average velocity is plotted as a function of depth. In cases where the observations cannot be taken from a well, estimates or calculations based on lithologic properties may be employed. In either instance the result is a working graph such as that illustrated by Fig. 2 which is a hypothetical case prepared for this discussion.

The utility of this graph may be enhanced by the preparation of of other graphs upon which may be read directly values of depth below the weathering for observed reflection arrival times. These graphs also give depth values for a range of spreads between shot point and mean recorder station. It is seen from this practice that all depth calculations are customarily based on the assumption: *the velocity of vertical travel to any reflection horizon varies only according to depth below the surface,* or

$$V_z = f(z). \tag{6}$$

Experience shows that the characteristics of the geologic formations encountered in the reflection path of travel may have a greater effect on the velocity for this path than the thickness of the overlying

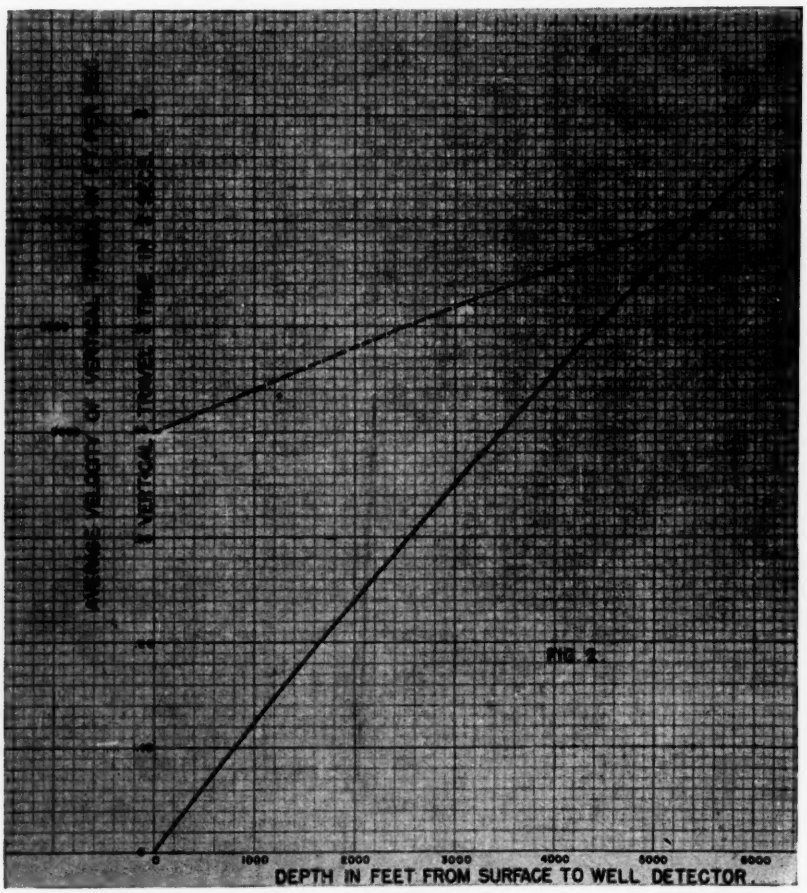


FIG. 2. Assumed vertical velocity vs. depth relation.

section. For example, 4,000 ft. of section might exhibit a velocity of, say 9,200 ft. per second taken at the top of a geologic column, while 9,600 ft. per second might represent the true velocity for the basal 4,000 ft. of the same column, from which 1,000 ft. have been removed from the top by erosion.

To eliminate this effect of surface topography it is proposed first

to determine by measurement the velocity function of the entire geologic section. If measurements are not available then estimates may be made from lithologic characteristics. Beginning at a point where the youngest known geologic formations are present, the travel time of seismic waves through the section is determined. It is then proposed to distribute the velocity function so obtained with respect to the portion of the geologic section embraced in the reflection path at each station. Figure 2 shows an example of the travel time and velocity function selected for this discussion.

The equation for these curves follows:

$$T = 2.5 \log_e (8000 + .4Z) \tag{7}$$

where

T = vertical travel time from shot to detector in seconds.

Z = vertical separation in feet between shot point and detector.

From equation 7 the following may be derived:

$$V_{av.} = Z/T = Z/2.5[\log_e (8000 + .4Z)] \tag{8}$$

which is the upper curve of Fig. 2, in dashed line.

To substantiate the assumption that physical properties of rocks *in situ* are primarily responsible for the velocity of the path of travel, let us first regard the portion which each element of the geologic section contributes to the average. Any homogeneous formation will be found to have an individual, identifying velocity. If measured *in situ* this might be called the "instantaneous" velocity, or the formation velocity at the point. It may be defined as follows:

$$V' = dz/dt.$$

From this we may write

$$dt = dz/V'$$

and the total time of travel will be given by

$$T = \int_{z_1}^{z_2} dt = \int_{z_1}^{z_2} dz/V'$$

whereas the average velocity for the entire section from the surface to Z will be given by

$$V_{av.} = Z/T = Z \Big/ \int_0^{z_2} dz/V' \tag{9}$$

or

$$Z \Big/ \int_0^z dz/V' = Z/2.5[\log_e (8000 + .4Z)]$$

hence

$$V' = 8000 + .4Z. \tag{10}$$

In general terms this may be expressed as follows:

$$T = \int dt = \int_{z_1}^{z_2} dz/V'. \tag{11}$$

If

$$V' = V_0 + KZ$$

$$T = \int_{z_1}^{z_2} dz/(V_0 + KZ) = 1/K \log_e (V_0 + KZ) \Big]_{z_1}^{z_2} \tag{12}$$

and

$$V_{av.} = Z/T = Z \Big/ \int_{z_1}^{z_2} dz/V' = KZ/\log_e (V_0 + KZ) \Big]_{z_1}^{z_2}. \tag{13}$$

To make use of these relationships it is necessary but to choose appropriate limits Z_1 and Z_2 in equations 12 and 13.

If no erosion has taken place, Z_1 becomes zero, but for any other degree of erosion the remaining section of the geologic column will be embraced between the limits Z_1 and Z_2.

The use of this method in practice may appear cumbersome since the depth of reflecting horizon would have to be known before the limit Z_2 could be selected. For this reason it is convenient to make up graphs of

$$V_z = f(z)$$

and $T=f(z)$ for varying degrees of erosion.

Each of these graphs corresponds to a selected value of Z_1. Figure 3 shows a plot of velocity-depth curves computed in this fashion. The basis of computation is the full section velocity function shown in Fig. 2, from which erosion at intervals of 200 ft. has been assumed. Fig. 4 is a plot of the values for time-depth curves at levels of erosion spaced at 200 ft. intervals.

From these graphs it is interesting to note the improvement in the determination of depths by this method. A reflection arrival time of

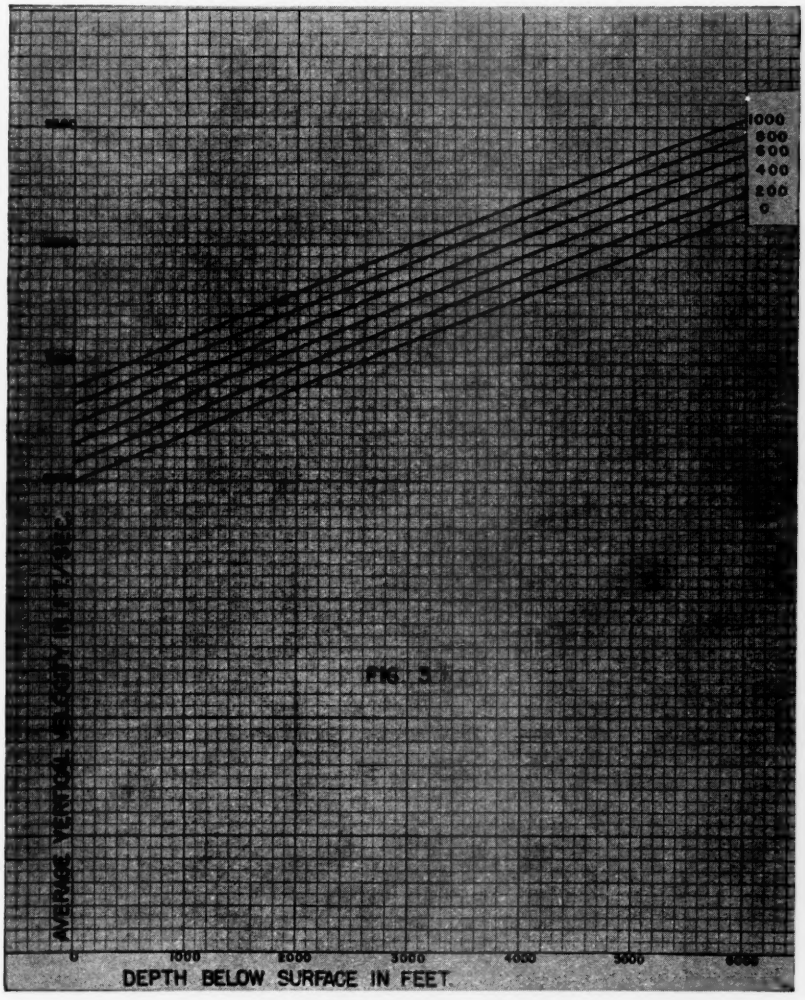


FIG. 3. Curves of vertical velocity vs. depth for 200 ft. increments of erosion.

1.000 seconds without erosion yields a depth of 4430 ft. while at 400 ft. of erosion the same time will yield a depth of 4600 ft. An error of 170 ft. has been avoided by this correction.

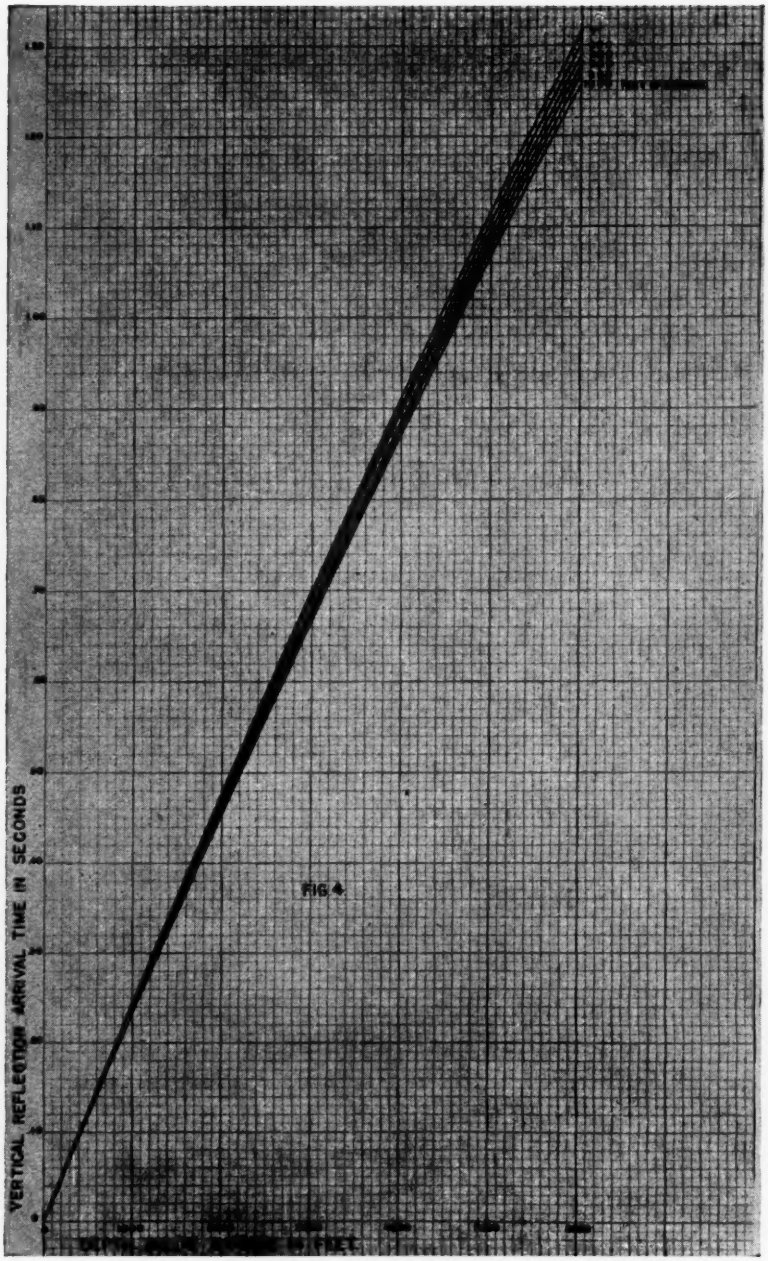


FIG. 4. Time vs. depth curves for 200 ft. increments of erosion.

This procedure is also of aid in correcting the measurement of intervals between two reflecting horizons. At a station of no erosion, reflections arriving at .912 seconds and 1.154 seconds give depths of 4,000 ft. and 5,200 ft. respectively. At a station where 1,000 ft. of erosion had taken place, the corresponding reflections are:

$T_1 = .668$ seconds

$Z_1 = 3000$ feet

$T_2 = .910$ seconds

$Z_2 = 4200$ feet $\Delta Z = 1200$ feet

at these times upon reading from the "no erosion" chart, the depths would have been:

$Z_1 = 2850$ feet

$Z_2 = 3990$ feet $\Delta Z = 1140$ feet, an error in interval of sixty feet.

The principle suggested herein may be employed to advantage in provinces overlain by great thicknesses of drift materials. In the glaciated regions of northern United States and of Canada the vertical velocity through the drift has been found of widely different value than that of subjacent Paleozoic sediments. A division of reflection travel path into two portions as indicated by the geologic differentiation offers a ready means of translating reflection time into true subsurface depths. The method will be found of equal value in provinces overlain with thick layers of high speed materials, such as the Edwards Plateau of Texas.

DETERMINATION OF DENSITY FOR REDUCTION OF GRAVIMETER OBSERVATIONS*

L. L. NETTLETON**

ABSTRACT

This paper outlines a method whereby the density factor used in the Bouguer correction for elevation of a gravity station may be determined. Frequently in the past it has been the practice to assign a density factor based on measurements made upon samples of surface materials in such manner as to give the density in situ, depending upon the judgment of the field man to select samples representative of the near-surface materials. At best, this is a cursory determination which only fortuitously might lead to the correct density for large topographic features. The method outlined here in effect weighs the topography by gravimeter observations taken along a profile crossing the feature. From these data the effective density of the material comprising the topographic feature is determined by a simple graphical method.

Development of gravimeters in the past three years has produced field instruments which make reliable observations of gravity differences to a precision of 0.1 mg. or better. If the final gravity map is to retain all of the precision of the field observations, it is necessary that all reductions be made to a precision somewhat better than that of the original field observations themselves.

The elevation correction includes two factors; that is, (1) a correction for the so called "free air" effect which takes account of the fact that the attraction of the earth on points at different elevations varies appreciably because of the variation in their distance from the center of the earth; the theoretical value of the coefficient for this term is accurately known from the size and mass of the earth, but the actual value varies slightly from this theoretical value,[1] and (2) the "Bouguer"[2] correction which takes account of the attraction on the station of the material between the elevation of the station and that of the base point to which the elevation corrections are made; this term depends upon the density of the surface material.

* Paper read at Annual Meeting, Oklahoma City, Oklahoma, March 21, 1939.

** Gulf Research and Development Corporation, Pittsburgh, Pa.

[1] Sigmund Hammer, Investigations of the Vertical Gradient of Gravity, Trans. of the Am. Geophys. Union, 19th Annual Meeting (1938), pp. 72–82.

[2] The "Bouguer" correction as used in this paper is the correction for the attraction of the topography as approximated by an infinite horizontal slab of thickness h, where h is the difference between the elevation of the station and that of the base level to which the reductions are made. If this approximation is inaccurate a "terrain correction" must be made, such as is described in the following paper in this journal.

The coefficient for the Bouguer correction is

0.0127σ in mg. per ft., or

0.0418σ in mg. per meter.

where σ is the density of surface material (within the elevation range of the topography). From these coefficients it is evident that if stations differ in elevation by, say, 100 ft., an error in density of 0.1 cgs. units will make an error of about .13 mg. in the reduction of the station. The precision with which the density of the surface material is required depends, of course, upon the range in elevation of the gravity stations. From the example just given it is evident that if the topography is such that the stations may vary by 100 ft. or more in elevation, the density should be known to better than 0.1 cgs. unit if the reductions are to retain a precision greater than 0.1 mg.

Density can be determined by actually making density measurements of samples of the surface material. This, however, is not very satisfactory because the densities of individual samples usually vary over a wide range so that a large number of samples is required for a reliable average value. Also, it is often difficult to get samples which are far enough below the weathered surface to be typical of the rock material within the range of the topography. This is particularly true if there are alternating hard and soft members of the surface formations. The soft members (usually shales) may be covered and the natural outcrops are the hard members, which commonly are typical of only a small fraction of the total section.

The purpose of this report is to describe a method which has been found quite satisfactory for determining density by use of the gravimeter itself. The method seems quite obvious and probably is being used by others but the writer has been unable to find reference to it in geophysical literature.

The density is measured simply by making a special traverse of gravimeter stations across a topographic feature, reducing these stations for several different densities, and finding the density value for which the reduced curve has a minimum correlation with the topography. In this method the sample is an entire topographic unit and the value obtained is the average density of all material within the elevation range of the gravity traverse.

It is essential that the topographic feature selected for a density profile should have at least one reversal; that is, it should be either over a hill or across a valley. A simple slope cannot be used because it is not possible to separate the contribution of density to the slope

of the observed gravity profile from a possible regional slope of the properly reduced gravity curve. A hill seems to be somewhat preferable to a valley because the density is more apt to be uniform and typical of the topography as a whole, for valleys frequently contain alluvial material, the density of which is different from that of the general rock section. Rather gentle topographic slopes are preferable because steep features usually will require terrain corrections if the precision of the reduction is to be held to considerably better than 0.1 mg. However, steep features can be used if adequate terrain corrections are made. Obviously, the hill or valley selected must not be associated with geologic structure which might cause a gravity anomaly coextensive with the topographic feature.

In general, the relief of the topographic feature measured should be comparable with the average relief of the topography within the general area for which the density is desired. From an operating standpoint, the ideal feature for a density profile is a gentle hill with a relief of the order of 50 to 150 ft. and a width of $\frac{1}{2}$ mile to one mile preferably, of course, crossed by a road. Relief of this magnitude will require little, if any, terrain correction if the slopes are regular. Gravity stations should be set at such intervals that there are several stations to define the gravity curve across the hill or valley. The gravity differences may be determined with reference to one of the stations of the traverse itself. They should be as accurate as feasible. The relative elevations of the stations, of course, must be determined to a precision of about 1 ft. or better.

The analysis of a density traverse consists primarily of plotting profiles of the elevations and of the gravity values with the usual reductions for latitude and free air corrections and with different curves for the Bouguer corrections made with different densities. Under favorable conditions a quite definite selection can be made of the density which comes closest to giving reduced gravity values on a straight line across the topographic feature. Frequently there are some stations which do not fit into a smooth curve for any density, having departures up to a few tenths mg. Our experience indicates that these irregularities are caused by real inhomogeneities in the material as check observations have confirmed the gravity differences. In such cases, it seems best to ignore such points and use, as the density, the value which will give the straight line (if the profile is short, or a smooth curve if long) for which the departures of individual points are a minimum.

If the density profile crosses a geologic contact it is possible that different parts of the curve will indicate a real change in the density of the material sampled. For this reason, it is sometimes preferable to run density profiles along the strike and avoid crossing geologic contacts if suitable topographic features can be found, and to make separate profiles on exposures of beds of different lithology.

The density profile has a theoretical advantage over the sample method of determining densities. In the sample method the reduction depends on using correct values for the free air coefficient and for the calibration of the gravimeter so that all values are in consistent units (milligals). However, the actual free air coefficient (i.e., the vertical gradient of gravity) may depart by a few per cent from the theoretical value because of large regional gravity anomalies. Also, the instrument calibration may be in error. However, the density determined by the density profile method is that which reduces the *apparent* elevation effects. The errors mentioned, if large, will lead to density values which are in error with respect to the true density of the rock material within the topography, but this error will compensate for the instrumental and vertical gradient errors mentioned. This is true only to the extent that vertical gradient, density, and instrument calibration are constant over the entire area for which a given density profile is considered typical.

Figures 1 to 6 show typical density profiles observed in routine field work using the Hoyt[3] gravimeter. This series is selected to demonstrate rather unexpected variations of surface density indicated by such profiles. The six localities are in Caddo and Washita Counties, Oklahoma, all in 9 and 10N, the series running from east to west. The first four are all on the unit shown on the State Geologic Map as the Day Creek-Whitehorse formation, but they show a progressive decrease and then a slight increase of density in going westward as successively younger parts of this formation outcrop. Apparently there is an abrupt change of density between this formation and the overlying Cloud Chief gypsum, indicated by the change from a density of 2.1 (Fig. 4) to 2.7 (Fig. 5). This high density probably is caused by anhydrite and dolomite in the Cloud Chief formation. Farther west the younger Quartermaster formation shows a more "normal" density of 2.4. (This value is called "normal" because it has been shown by density profiles in widely scattered places in southern and southwestern Oklahoma.)

[3] Archer Hoyt, U. S. Patent 2,131,737, October 4, 1938.

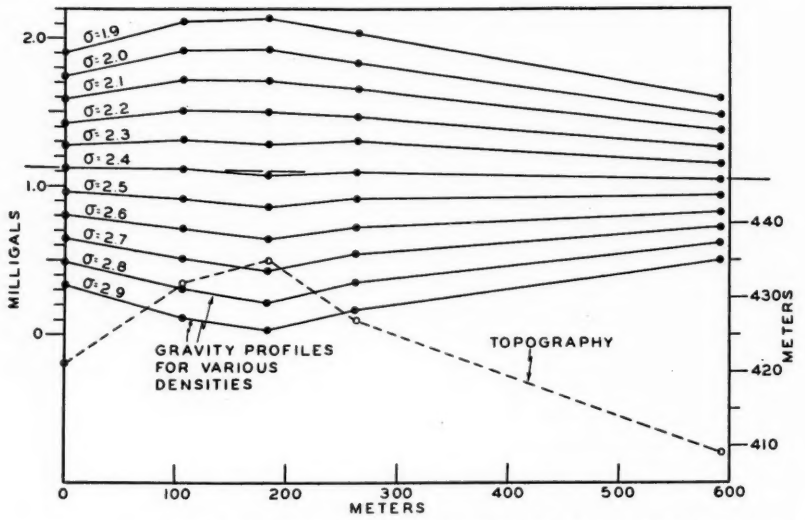


FIG. 1. Density Profile, 10N-10W, Caddo, County, Oklahoma. Whitehorse Sandstone, Indicated Density, 2.4.

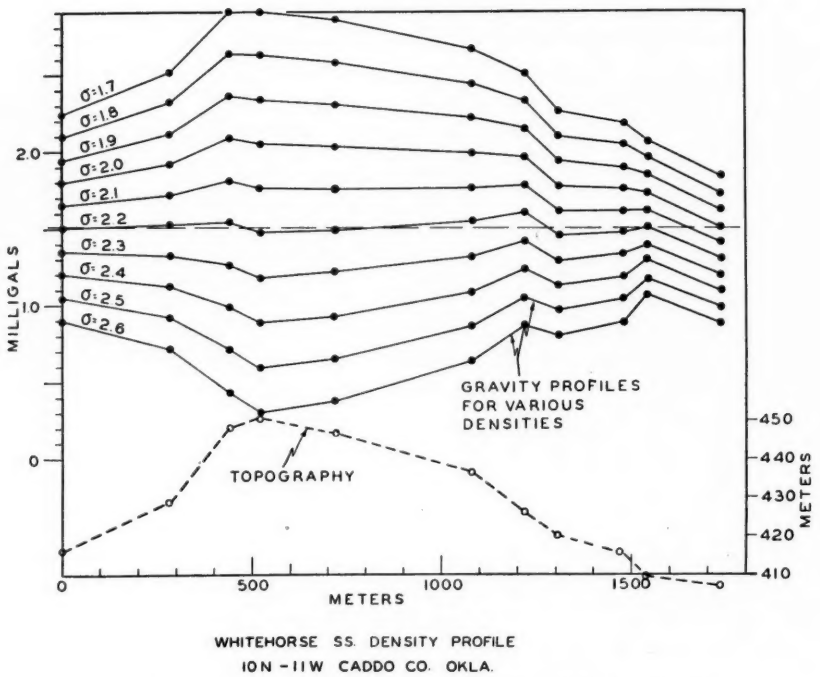


FIG 2 Density Profile, 10N-11W, Caddo County, Oklahoma. Whitehorse Sandstone, Indicated Density, 2.2.

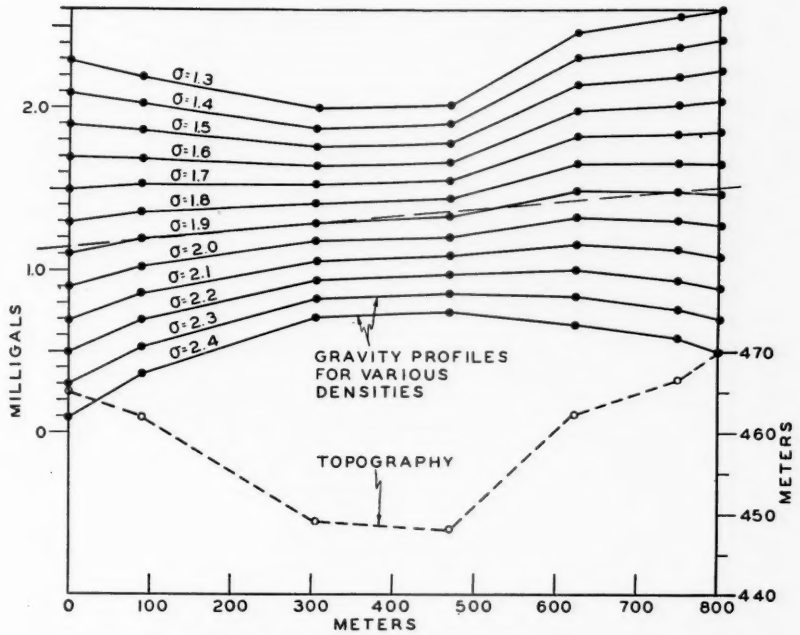


FIG. 3. Density Profile, 10N-12W, Caddo County, Oklahoma. Whitehorse Sandstone, Indicated Density, 1.9.

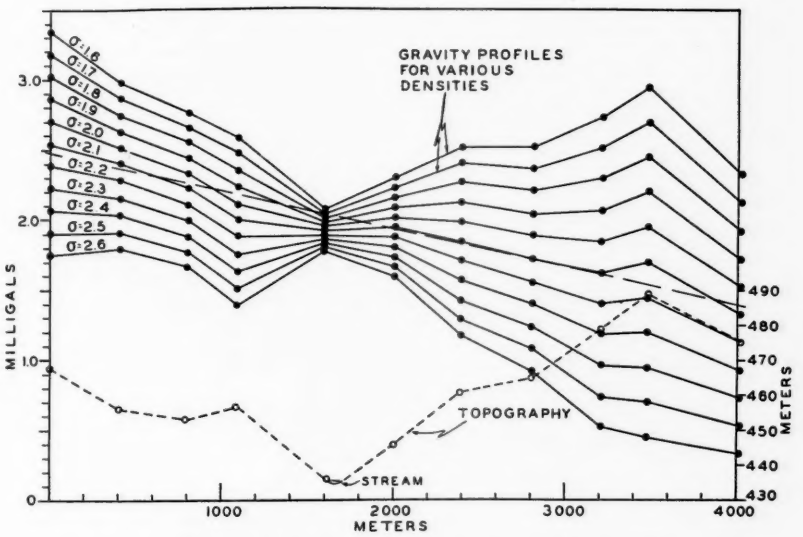


FIG. 4. Density Profile, 10N-13W, Caddo County, Oklahoma. Whitehorse Sandstone, Indicated Density, 2.1.

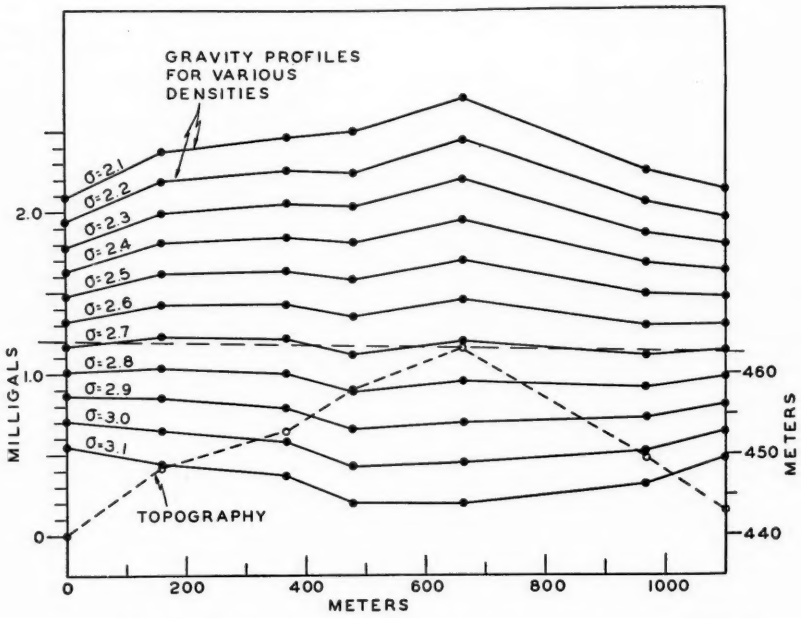


FIG. 5. Density Profile, 9N-15W, Washita County, Oklahoma. Cloud Chief Gypsum, Indicated Density, 2.7.

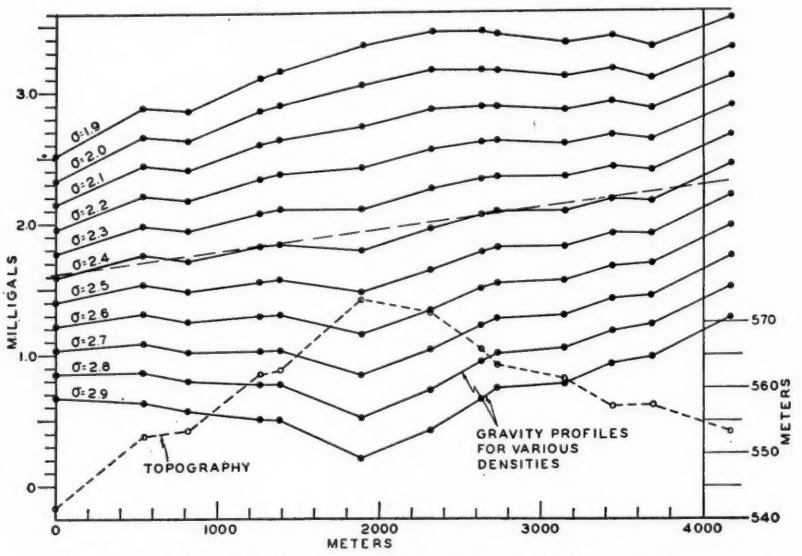


FIG. 6. Density Profile, 10N-19W, Washita County, Oklahoma. Quatermaster Formation, Indicated Density, 2.4.

In cases where a material of one density overlaps material of a different density, it may be necessary to make more complex reductions of the gravity values. A good example of this is the overlap of the Trinity sandstone over the Permian in southern Carter County, Oklahoma. The Trinity sandstone has a density of about 2.1 and the underlying Permian a density of about 2.4. An estimate was made of the general configuration and elevation of the contact at the base of the Trinity. Then the Bouguer correction was calculated with a density of 2.1 for the estimated thickness of Trinity under the station location and a density of 2.4 for the thickness of the Permian between the bottom of the Trinity and the base elevation to which all the stations were referred.

Another case of complex densities occurs at the Llano Estacado escarpment in eastern New Mexico. The surface density above the escarpment is about 2.0 and that below the escarpment is about 2.4. In this case the relief of the escarpment is around 200 ft. When stations are reduced with a single density there is a distinct discontinuity in the reduced gravity map at the escarpment. This situation was handled by estimating from gravity profiles across the escarpment the proportions of the topographic relief to which the densities measured above and below the escarpment should be assigned in order that the reduced gravity would be smooth across the topographic feature. When complex reductions were made for the thicknesses with the two densities thus indicated, a satisfactory reduced gravity picture could be made across this rather rugged topographic feature.

The writer is indebted to Drs. P. D. Foote and E. A. Eckhardt for permission to publish this paper and to Mr. W. K. Hastings, party chief, and his gravimeter field party who are responsible for the field results used for the illustrations.

TERRAIN CORRECTIONS FOR GRAVIMETER STATIONS*

SIGMUND HAMMER**

ABSTRACT

In this paper the correction for the gravitational attraction of the topography on a gravity station is considered as consisting of two parts; (1) the restricted but conventional "Bouguer correction" which postulates as a convenient approximation that the topography consists of an infinite horizontal plain, and (2) the "Terrain correction" which is a supplementary correction taking into account the gravitational effect of the undulations of the terrain about the plane through the gravity station. The paper illustrates the necessity of making terrain corrections if precise gravity surveys are desired in hilly country and presents terrain correction tables with which this quantity may be determined to a relative accuracy of one-tenth milligal. This accuracy is required to fully utilize the high instrumental precision of modern gravimeters.

INTRODUCTION

Applications of the gravity method of geophysical prospecting in the search for small, local, geological structures require very precise data. To supply this need gravimeters have been developed or improved to the point where the probable error of the observed gravity values is of the order of 1/10 mg. or even less[1,2,3,4] To fully utilize this high instrumental precision it is obvious that corrections for the several non-significant influences, which are present in the observed gravity values, must be of the same order of accuracy. One of the important non-significant influences is the gravitational attraction of the topography in the vicinity of a gravity station. This so-called "topographic correction" will be considered, by definition, in the present paper to consist of two parts; (1) the "Bouguer correction" which postulates as a convenient approximation, that the topography consists of an infinite horizontal plain, and (2) the "Terrain correction" which evaluates the error in the Bouguer correction due to undulations of the terrain. The purposes of this paper are (a) to illustrate the necessity of making terrain corrections if precise gravity surveys are desired in hilly country, and (b) to present

* Published by permission of the Gulf Research & Development Co., Pittsburgh' Pa.

** Gulf Research & Development Co., Pittsburgh, Pa.

[1] E. A. Eckhardt, Geophysics 1, pp. 292–293 (1936) (abstract).

[2] D. C. Barton and W. T. White, Trans. Am. Geophys. Union, Part I, pp. 106–107 (1937).

[3] A. Graf. Zeits f. Geophys. *14*, pp. 152–172 (1938).

[4] H. Hedstrom, A.I.M.E. Tech. Publ. No. 953 (1938).

tables with which the terrain correction may be determined to the accuracy merited by the precision of modern gravimeters.

THE CORRECTION FOR TOPOGRAPHY

A common procedure in gravity prospecting is to correct for the attraction of the topography by use of an approximate value "B" calculated from the simple Bouguer formula

$$B = 2\pi\gamma\sigma(H - H_0) \qquad (1)$$

where $H-H_0$ is the elevation of the gravity station above the level datum

σ is the density of the surface soil or rock

γ is the gravitational constant.

This formula calculates the gravity effect of the matter between a horizontal plane through the field station and the horizontal elevation-datum-plane on the assumption that the space between these two planes out to an infinite radius is uniformly filled with matter if the station is above the datum plane, or is uniformly empty if the station is below this plane.[5] (See Fig. 1). Subtracting this quantity (algebraically) from the observed gravity value amounts to removing the *assumed* amount of matter in the infinite flat plate if the station is above the datum plane or to completely filling up this space if the station is below the datum plane so as to reduce, in effect, the surface of the ground to the plane through the elevation datum.

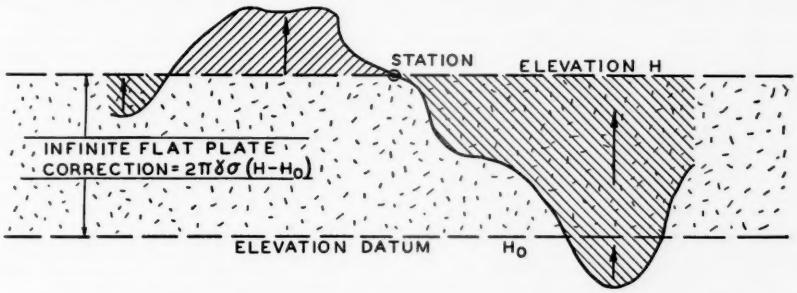


FIG. 1. Schematic diagram of the Bouguer correction, illustrating residual gravitational effects due to undulating terrain.

[5] For an excellent brief statement of the nature of the Bouguer reduction see Hayford and Bowie, U.S.C. & G.S. Special Publication No. 10, p. 75 (1912). These authors define the "Bouguer Correction" in the more general sense which is equivalent to our "Topographic Correction."

Undulations of the terrain are completely ignored in this Bouguer correction. Let us consider the error involved. First we see in Fig. 1 that the Bouguer formula overestimates the gravitational attraction of the actual mass below the station because it ignores the voids in this space. Therefore the corrected gravity value obtained by subtracting the approximate Bouguer correction will tend to be too low. Second, the upward component of the gravitational attraction of the mass

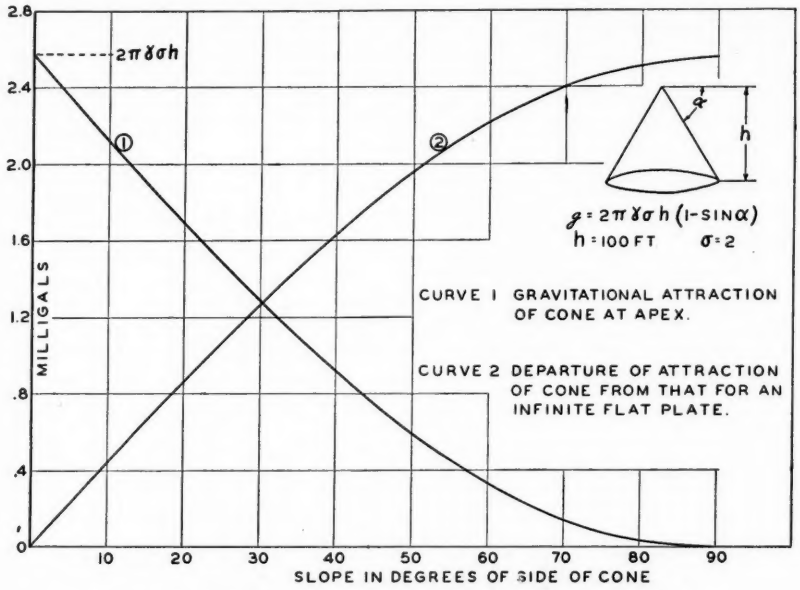


FIG. 2. Gravitational attraction of an idealized hill, illustrating the magnitude of the error in the Bouguer correction.

above the plane through the station, which tends to lower the observed gravity value, is not removed by the Bouguer correction. Thus, topographic elevations above and depressions below the station both act in the same sense and the gravity value corrected by the Bouguer formula will always be too low. Corrections for the effect of undulations of the terrain with respect to the station elevation plane will therefore always be positive.

Possible magnitudes of the terrain correction (as defined in this paper) are illustrated in Figs. 2 and 3. Figure 2 shows an idealized hypothetical case in which a gravity station is situated at the apex of a conical hill, which in turn is located upon a flat plain. Curve 1 shows

the decrease in the gravitational attraction of the hill as the sides become steeper. The attraction calculated by the Bouguer formula is the ordinate of curve 1 at $\alpha=0$. Curve 2 shows the error in the Bouguer formula, that is the terrain correction, as a function of the steepness of the hill. For example, if the slope of the hillside is 30° the Bouguer correction is twice too large.

Fig. 3 shows an actual example of a gravimeter profile across a very steep topographic feature, Sierra Madera (also known as

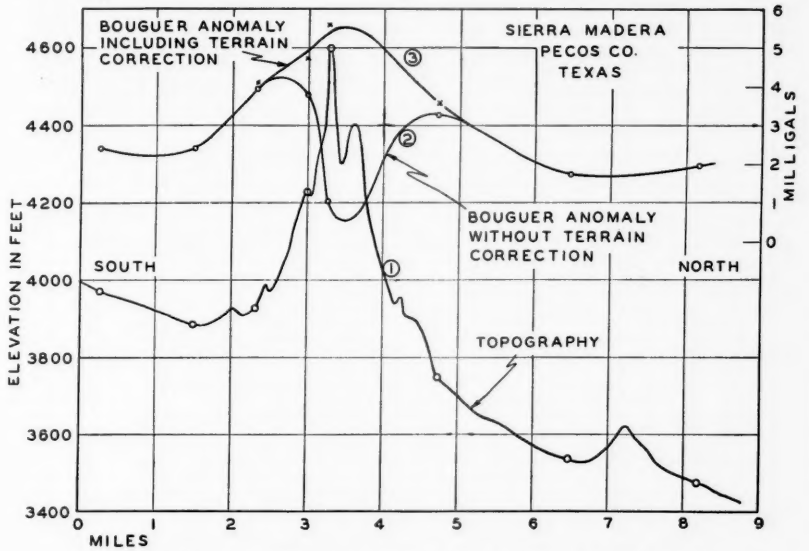


FIG. 3. Gravimeter profile across Sierra Madera, Pecos County, Texas, illustrating the importance of terrain corrections.

Madera Mountain), in Western Pecos County, Texas, which is known to be a sharply uplifted geological structure. Curve 1 depicts the topography. Curve 2 is the gravity profile (Bouguer anomaly) as reduced with the ordinary Bouguer correction, and curve 3 is the gravity profile after applying terrain corrections. The terrain corrections in this case amount to several milligals. It is clear that the interpretations of the two gravity profiles will differ fundamentally. Admittedly, this example is an extreme one for ordinary gravity prospecting but we must conclude that terrain corrections cannot be disregarded if precise gravity surveys are desired in hilly country.

Having demonstrated the importance of the terrain correction to gravity stations in hilly country, we consider next the method of

evaluating it. By its very definition it is clear that the terrain correction depends upon the details of the topography. Therefore, a topographic map, or the equivalent, of the vicinity of the gravity station is required. The area about the station is divided into zones

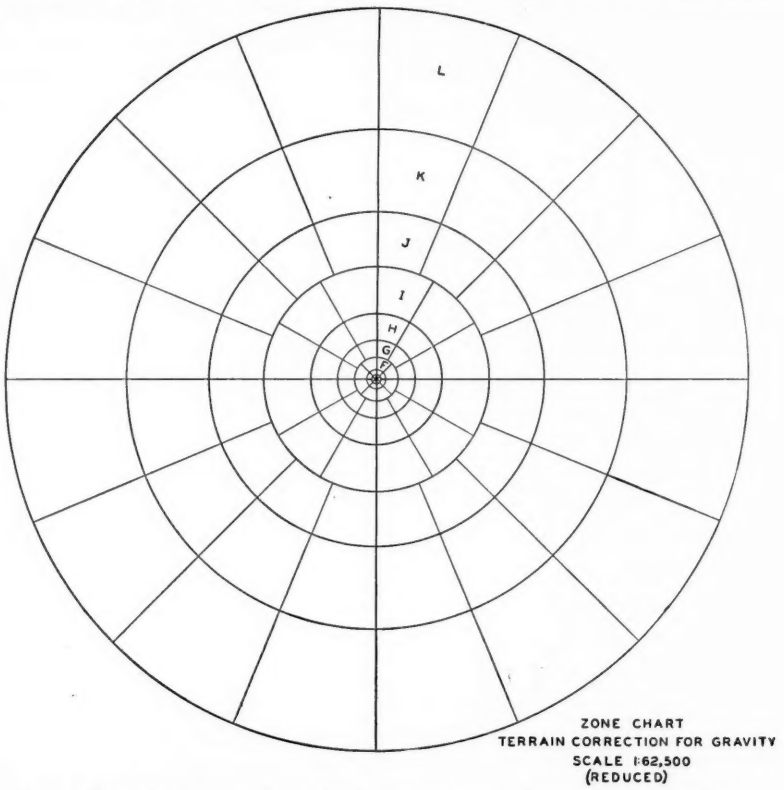


FIG. 4. Zone chart for use in evaluating terrain corrections at gravity stations.

and compartments, for example, by laying a transparent terrain correction zone chart, such as that shown in Fig. 4, upon the map and centering it at the gravity station. The average departure without regard to sign of the topography in each compartment from the plane through the station is then determined* and the terrain cor-

* Since the sign of the terrain correction (as defined in this paper) depends only on the absolute value of the departure of an element of the topography from the plane through the station, and not on its sign (that is, whether it is above or below the plane) it follows that the difference between the simple average elevation in each compartment and the station elevation cannot be used, *in principle*, if the terrain within any one com-

rection corresponding to this average departure is evaluated for each compartment by means of tables calculated for that purpose. Finally these terrain corrections are summed over all the zones in which there are appreciable effects.

TERRAIN CORRECTION TABLES

A number of terrain correction tables have been published[6,7,8] for geodetic and regional gravity work. However, the author knows of no previously published tables which are sufficiently precise for modern gravity prospecting needs. The tables presented in this paper have been designed especially for this use after experience extending over a number of years with terrain correction calculations.

The present tables were modelled after those by Hayford and Bowie[6,7] but are more precise and have been modified in principle to evaluate, not the total topographic correction, but only the error in the Bouguer correction as discussed above.* This modification permits relatively larger compartments in the distant zones, for a given precision, and thus reduces the labor involved in the use of the tables. However, to attain the precision desired the compartments in the zones near the station are smaller in the present tables than in those by Hayford and Bowie. Another important advantage of the modification in the principle is that it is necessary to use the tables in moder-

partment consists of elements both above and below the station. Thus, theoretically, if the topography within one compartment consists of a hill above the station and a valley below the station, the average departure must be determined as if the topography consisted of two hills or two valleys. However, in practice, it turns out that the terrain effect in such a compartment is ordinarily zero. Therefore, the mathematically rigorous but cumbersome procedure outlined above may usually be replaced by the much more rapid procedure of estimating the average elevations in all the compartments (irrespective of whether the topography in any one compartment is above and below the station) and then calculating the departures of these simple average elevations from the station elevation. This would not be true, in general, in extremely rugged topography of large relief but even then the complication may usually be avoided by rotating the zone chart to a different azimuth. The azimuth must, of course, be maintained while reading the elevations in all the compartments of any one zone.

[6] Hayford and Bowie, *loc. cit.*, pp. 13–53.

[7] Hayford and Bowie, U.S.C. & G.S. Spec. Publ. 40, pp. 11–18 (1917).

[8] Bullard, Philos. Trans. Roy. Soc. London A235, pp. 486–491 (1936).

* Bullard's tables (*loc. cit.*) are also of this type. His paper contains a detailed discussion of the advantages of this modification. A recent search in the literature reveals the historically interesting fact that this method was described by F. R. Helmert in 1884 ("Theorien der höheren Geodäsie," Vol. II pp. 169–172) and was called "the ordinary method" by F. A. Venning-Meinesz in 1923 ("Observations de Pendule dans les Pays-Bas." Publ. de la comm. géod. néerlandaise, p. 141).

TERRAIN CORRECTION TABLES FOR GRAVITY

Each zone is a circular ring of given radii (in feet) divided into 4, 6, 8, 12, or 16 compartments of arbitrary azimuth. "h" is the mean topographic elevation in feet (without regard to sign) in each compartment with respect to the elevation of the station. The tables give the correction "T" for each compartment due to undulations of the terrain in units of 1/100 mg. for density (σ) = 2.0. This correction, when applied to Bouguer anomaly values which have been calculated with the simple Bouguer correction, is always positive.

Zone B 4 compartments 6.56 to 54.6*		Zone C 6 compartments 54.6 to 175		Zone D 6 compartments 175 to 558		Zone E 8 compartments 558 to 1280		Zone F 8 compartments 1280 to 2936		Zone G 12 compartments 2936 to 5018	
$\pm h$ (ft.)	T	$\pm h$ (ft.)	T	$\pm h$ (ft.)	T	$\pm h$ (ft.)	T	$\pm h$ (ft.)	T	$\pm h$ (ft.)	T
0 to 1.1	0	0 to 4.3	0	0 to 7.7	0	0 to 18	0	0 to 27	0	0 to 58	0
1.1– 1.9	0.1	4.3– 7.5	0.1	7.7– 13.4	0.1	18– 30	0.1	27– 46	0.1	58– 100	0.1
1.9– 2.5	0.2	7.5– 9.7	0.2	13.4– 17.3	0.2	30– 39	0.2	46– 60	0.2	100– 129	0.2
2.5– 2.9	0.3	9.7– 11.5	0.3	17.3– 20.5	0.3	39– 47	0.3	60– 71	0.3	129– 153	0.3
2.9– 3.4	0.4	11.5– 13.1	0.4	20.5– 23.2	0.4	47– 53	0.4	71– 80	0.4	153– 173	0.4
3.4– 3.7	0.5	13.1– 14.5	0.5	23.2– 25.7	0.5	53– 58	0.5	80– 88	0.5	173– 191	0.5
3.7– 7	1	14.5– 24	1	25.7– 43	1	58– 97	1	88–146	1	191– 317	1
7 – 9	2	24 – 32	2	43 – 56	2	97–126	2	146–189	2	317– 410	2
9 –12	3	32 – 39	3	56 – 66	3	126–148	3	189–224	3	410– 486	3
12 –14	4	39 – 45	4	66 – 76	4	148–170	4	224–255	4	486– 552	4
14 –16	5	45 – 51	5	76 – 84	5	170–189	5	255–282	5	552– 611	5
16 –19	6	51 – 57	6	84 – 92	6	189–206	6	282–308	6	611– 666	6
19 –21	7	57 – 63	7	92 –100	7	206–222	7	308–331	7	666– 716	7
21 –24	8	63 – 68	8	100 –107	8	222–238	8	331–353	8	716– 764	8
24 –27	9	68 – 74	9	107 –114	9	238–252	9	353–374	9	764– 809	9
27 –30	10	74 – 80	10	114 –120	10	252–266	10	374–394	10	809– 852	10
		80 – 86	11	120 –127	11	266–280	11	394–413	11	852– 894	11
		86 – 91	12	127 –133	12	280–293	12	413–431	12	894– 933	12
		91 – 97	13	133 –140	13	293–306	13	431–449	13	933– 972	13
		97 –104	14	140 –146	14	306–318	14	449–466	14	972–1009	14
		104 –110	15	146 –152	15	318–331	15	466–483	15	1009–1046	15

* Radii of the zone in feet.

Zone H 12 compartments 5018 to 8578		Zone I 12 compartments 8578 to 14,662		Zone J 16 compartments 14,662 to 21,826		Zone K 16 compartments 21,826 to 32,490		Zone L 16 compartments 32,490 to 48,365		Zone M 16 compartments 48,365 to 71,996	
$\pm h$ (ft.)	T	$\pm h$ (ft.)	T	$\pm h$ (ft.)	T	$\pm h$ (ft.)	T	$\pm h$ (ft.)	T	$\pm h$ (ft.)	T
0 to 75	0	0 to 99	0	0 to 167	0	0 to 204	0	0 to 249	0	0 to 304	0
75– 131	0.1	99– 171	0.1	167– 290	0.1	204– 354	0.1	249– 431	0.1	304– 526	0.1
131– 169	0.2	171– 220	0.2	290– 374	0.2	354– 457	0.2	431– 557	0.2	526– 680	0.2
169– 200	0.3	220– 261	0.3	374– 443	0.3	457– 540	0.3	557– 659	0.3	680– 804	0.3
200– 226	0.4	261– 296	0.4	443– 502	0.4	540– 613	0.4	659– 747	0.4	804– 912	0.4
226– 250	0.5	296– 327	0.5	502– 555	0.5	613– 677	0.5	747– 826	0.5	912–1008	0.5
250– 414	1	327– 540	1	555– 918	1	677–1119	1	826–1365	1	1008–1665	1
414– 535	2	540– 698	2	918–1185	2	1119–1445	2	1365–1763	2	1665–2150	2
535– 633	3	698– 827	3	1185–1403	3	1445–1711	3	1763–2086	3	2150–2545	3
633– 719	4	827– 938	4	1403–1592	4	1711–1941	4	2086–2366	4	2545–2886	4
719– 796	5	938–1038	5	1592–1762	5	1941–2146	5	2366–2617	5	2886–3191	5
796– 866	6	1038–1129	6	1762–1917	6	2146–2335	6	2617–2846	6	3191–3470	6
866– 931	7	1129–1213	7	1917–2060	7	2335–2509	7	2846–3058	7	3470–3728	7
931– 992	8	1213–1292	8	2060–2195	8	2509–2672	8	3058–3257	8	3728–3970	8
992–1050	9	1292–1367	9	2195–2322	9	2672–2826	9	3257–3444	9	3970–4198	9
1050–1105	10	1367–1438	10	2322–2443	10	2826–2973	10	3444–3622	10	4198–4414	10
1105–1158	11	1438–1506	11	2443–2558	11						
1158–1209	12	1506–1571	12	2558–2669	12						
1209–1257	13	1571–1634	13	2669–2776	13						
1257–1305	14	1634–1694	14	2776–2879	14						
1305–1350	15	1694–1753	15	2879–2978	15						

FIG. 5. Tables for precise evaluation of terrain corrections at gravity stations.

ately hilly country for only a relatively small number of stations, and the labor involved in their use when needed is materially shortened. Also, the present tables are arranged in a form which eliminates interpolations and thus facilitates their use. With the present tables the office calculations of the terrain correction can be carried through in one-half to one hour per station.

The calculation of the tables was based upon the well known formula for the gravitational attraction of a vertical hollow cylinder at a point on the axis and in the plane of one end of the cylinder

$$g = 2\pi\gamma\sigma\left[R_2 - R_1 + \sqrt{R_1^2 + h^2} - \sqrt{R_2^2 + h^2}\right] \qquad (2)$$

where R_1 and R_2 are the inner and outer radii and h is the height of the cylinder (representing the average height of the terrain). The calculations were carried out by solving this equation for h in terms of the radii and an adopted unit gravitational attraction for one compartment.* To obtain the most nearly "square" compartments the ratio of the outer and inner radii (i.e., the radial length) of a zone was related to the width of the compartments in that zone by the condition $R_2/R_1=(n+\pi)/(n-\pi)$ where n is the number of compartments in the zone.

Finally, the author believes, on the basis of experience, that the areas of the various compartments in the present tables are maximum (i.e., that the total number of compartments is a minimum) consistent with practical accuracy in the determinations of the mean elevation of the terrain in the compartments. This last qualification depends, of course, upon the nature of the topography but tests indicate that the compartments in the present tables are small enough to give satisfactory accuracy even in very hilly country.

* For the convenience of anyone who might wish to make similar calculations, this formula, in the most convenient form, is

$$h_j = R_1\left[2a\left(\frac{a-1}{c}\right)\right]^{1/2} \times \left[j + \left\{\frac{a^2-3a+1}{2a\left(\frac{a-1}{c}\right)}\right\}j^2 - \left\{\frac{c^2}{2a}\right\}j^3 + \left\{\frac{c^2}{8a\left(\frac{a-1}{c}\right)}\right\}j^4\right]^{1/2} \div \left[\frac{a-1}{c} - j\right] \qquad (3)$$

where R_1=inner radius of the zone, a=ratio of outer to inner radius, $c=ng_0/2\pi\gamma\sigma R_1$, g_0=unit gravity effect, n=number of compartments in the zone, h_j=height of the cylindrical segment in one compartment which produces a gravity effect $j\times g_0$ and j is any number $\geqq 0$. In the present calculations $j=1/2, 3/2, 5/2 \ldots$ The formula is exact and not the first few terms of a series expansion.

The tables are given in Fig. 5 and comprise 12 zones "*B*" to "*M*" which in turn are subdivided into a total of 132 compartments. Zone *B* has an inner radius of 2 meters (6.56 feet) and zone *M* has an outer radius of $13\frac{1}{2}$ miles. Terrain at greater distances is not significant locally, except in extreme cases where adjacent stations are at greatly different elevations. In the present tables the area of a compartment in zone *B* is 2300 square feet (equivalent to 48 feet square) and the area of a compartment in zone *M* is 20 square miles (about $4\frac{1}{2}$ miles square). Zone *A*, the area within two meters of the station, is not given because only very extreme terrain conditions will give appreciable effects within this small area.* Curvature of the earth is ignored as its effect on the tabulated elevations is practically negligible within the area covered by the tables. (At the center of zone *M* the curvature amounts to 87 feet and is just on the verge of becoming appreciable).

The density of the surface material has been assumed, for the purpose of calculating the tables, to be 2.0. For another density σ the total terrain correction as evaluated by the tables must be multiplied by the factor $\sigma/2$. Gravity effects are tabulated to 0.001 and 0.01 mg. The reason for the two tabular intervals will be discussed later.

The precision with which the terrain correction may be obtained with the present tables is, of course, fundamentally dependent upon the adequacy of the topographic information available. The first elevation entries in the tables indicate roughly the required accuracy of the mean elevation in each compartment in the various zones. U.S.C.&G.S. topographic maps, where available, are generally adequate for the zones beyond one-fourth to one-half mile from the station, but in hilly country special level data near the station are ordinarily required. In moderately hilly country the tables may serve as a basis for judgment in the selection of station sites so as to avoid much of this special levelling.

* The only important case we need consider is that in which the station is located on a hillside. The terrain effect within a circle of radius R of a plain inclined at an angle θ from the horizontal and passing through the gravity station is

$$T_R = 2\gamma\sigma R[\pi - 2\cos\theta\, K(\sin\theta)] \qquad (4)$$

where $K(\sin\theta)$ is the complete elliptic integral of the first kind. Thus a terrain effect of 0.01 mg. (for $\sigma = 2.0$) within zone A requires a slope of $27\frac{1}{4}°$. A common modification of this case is one in which the station is located at the edge of an embankment or road cut. Then the sloping plain occupies only half the area of the first zone and the terrain effect is one-half of that given by equation 4. In this case a terrain effect of 0.01 mg. within zone *A* requires a slope of 38°.

Assuming, for the purpose of discussing the precision of the tables themselves, that completely adequate topographic maps are available and that the correct average elevation in each compartment is known, we note that a complete determination of a terrain correction involves 132 entries from the tables, each of which is subject to a maximum error of 1/200 mg. These reading errors are of a random nature, hence the Theory of Errors predicts a "probable" accumulative reading error in the terrain correction of 0.02 mg. For statistical reasons in individual cases the actual accumulative reading error will range both larger and smaller than 0.02 mg. but in only rare cases will it exceed 0.1 mg. which is the desired precision.

The 1/100 mg. tabular interval considered above is not adequate in topography of low relief however. Consider, for example, an hypothetical case in which the terrain in each of the compartments has an average height relative to the station elevation just short of that producing a terrain effect of 0.005 mg. A table in which the first entry corresponds to 1/100 mg. effect would then yield a zero terrain correction whereas, actually, since the effects accumulate without cancellation, the correction should be $0.005 \times 132 = 0.7$ mg. To overcome this circumstance the first entries in the present tables include terrain effects down to 0.0005 mg. per compartment so that the maximum terrain correction which may escape evaluation by the tables is 0.07 mg. The error which arises from the tables themselves is thus less than 1/10 mg. and therefore the terrain correction, for the area covered by the tables, may be determined to this accuracy if adequate topographic information is available.

CONCLUSION

Gravimeter surveys in hilly country are subject to errors which may be much larger than the probable errors of the unreduced gravity values unless accurate corrections are made for the non-significant gravitational effects of the undulating topography. These corrections may be evaluated with an accuracy comparable to the instrumental precision of modern gravimeters by use of the terrain correction tables presented in this paper in conjunction with adequate topographic information about the vicinity of the gravity stations. With this additional technique it should be possible to extend gravimeter prospecting into hilly country without appreciable loss in precision.

The author expresses his thanks to Dr. Paul D. Foote and Dr. E. A. Eckhardt for permission to publish this paper.

CONCENTRATIONS OF HYDROCARBONS IN THE EARTH*

EUGENE McDERMOTT†

ABSTRACT

An hypothesis of the origin and accumulation of oil and gas fields, arrived at from the data of soil analysis, is presented.

This hypothesis also offers an explanation of the quite different concentrations of subsurface waters in different geologic provinces.

Furthermore, it seeks to explain the variation of type of accumulation with respect to depth below the surface and deformation of the sediments in which the accumulation occurs.

Lastly, the value of the method of soil analysis as an exploration device is indicated.

Historically, the Russian investigators have published a considerable amount of data covering the results of their gas analysis work. In this work samples of air with contained gases were collected at shallow depths in the earth and analyzed for methane and the heavier hydrocarbon gases. It is not definitely known to what extent the various constituents were separated. Rosaire, about two years ago, made the forward step of taking samples of the soil itself and extracting the occluded gases in the laboratory, and undoubtedly made considerable progress in separating and identifying some of the constituent gases. Rosaire also introduced an exploration method making use of a surface wax. Smith is using some soil analysis method which he has not disclosed.

We have succeeded in establishing the presence of unsaturated hydrocarbons such as ethylene in the soil in appreciable quantities. This is very significant as unsaturated hydrocarbons are considerably more reactive than either methane or ethane. The saturated hydrocarbons such as methane and ethane are known as paraffins, which means without affinity. The unsaturated hydrocarbons such as ethylene are of the olefine family of hydrocarbons. The word olefine means oil forming. This immediately led to a series of investigations and experiments which resulted in the gathering of considerable data concerning the concentrations of hydrocarbons as well as minerals near the surface of the earth. From such observations an hypothesis was derived which in a very substantial manner accounts for the accumulations found near the earth's surface, as well as at depth.

* Paper read at Annual Meeting, March 23, 1939, Oklahoma City.

† President Geophysical Service, Inc. Dallas, Texas.

This hypothesis, evidence for which will be presented in this paper, the main stipulates as follows:

1—Genetically, the subsurface concentrations (oil and gas fields) and the near-surface concentrations of hydrocarbons are very much the same. Oil shales are included in this category.

2—The source materials of oil and gas fields are the hydrocarbon gases which are leaking from the basement complex, as well as buried coal deposits, that is vegetable matter that is being devolatilized.

3—The saturated hydrocarbons such as methane and ethane result in gas fields, whereas the unsaturated hydrocarbons such as ethylene are synthesized or polymerized to form oil fields.

4—These gases migrate essentially vertically. There is no great movement of oil in the original accumulation.

5—Whether an oil or gas field is formed depends principally on the permeability of the cap rock over a reservoir sand, and perhaps also to a more limited extent on the presence of certain catalyzers such as aluninum chloride.

6—As the permeability of a shale decreases with depth of burial and in regions of deformation, the volatility of the accumulations will increase with depth and in regions of deformation.

7—These gases in migrating to the surface transport quantities of the subsurface waters and the minerals dissolved in these waters.

Not only were hydrocarbon gases found to occur generally in the sedimentary areas investigated, but, in a way more significantly, they were found immediately on top of and in the basement rocks in the Llano-Burnet uplife in Texas and the Sierras in California. This established the basement rocks as a likely source of hydrocarbon gases. Furthermore samples of coal that were analyzed were found to contain large quantities of ethylene, ethane and methane. Also there is reason to believe that some of the gas seeps in East Texas are due to the escape of gases from buried lignite deposits. So it is but logical to conclude that both the basement rocks and the buried coal deposits (that is buried vegetable matter that is being devolatilized by pressure) are the sources of the gases from which our oil and gas fields are derived. It is not the author's intention to attempt to evaluate the relative contributions of these two sources nor to exclude other possible sources, as yet unmeasured, but he does wish to stress the assumption that so far as migration is concerned the gases seem to be the principal participants.

The gases in migrating to the surface are motivated by the force

of gravity due to the difference in density between them and the fluids of the earth. In a homogeneous isotropic formation this force is entirely vertical except for the forces of diffusion which are small because of the low solubility of the gases in water. A horizontal component of force comes into play only at the juncture of two formations of different permeabilities. The magnitude of the horizontal component of force will be a function of the dip of the plane of the interface between the two mediums. In a distance somewhat greater than the diameter of a bubble the gas will again be in a homogeneous medium and consequently the resulting force will again be vertical. Even with large differences in permeabilities between a sand and an overlying shale there will be very little horizontal movement of the gases at the interface. This is in entire agreement with observations made near the earth's surface. After having crossed many contacts between sands and shales the concentration of the gases and the resulting liquids and solids near the surface are found to occur in a relatively narrow band. Although shales are regarded as being impermeable, it must be borne in mind that this is purely relative. Their permeability is of a different order of magnitude from that of sands and of course in some instances limestones. In most cases the permeability of shale may be due to vertical fissures. As the quantity of gas that passes through a medium is a function of time as well as permeability, given sufficient time large quantities of gas may migrate through the so-called impermeable shales as a result of gravitational forces.

From the above mentioned migrating hydrocarbon gases both liquid and solid hydrocarbons will be formed near the surface of the earth. It is known that ethylene in the presence of chlorine, and especially aluminum chloride, will polymerize into heavier hydrocarbons and with the addition of sunlight will polymerize even at a faster rate. For this reason liquid hydrocarbons would be expected to predominate just below the surface, whereas the solid as well as liquid hydrocarbons should be found in quantities immediately at the surface where sunlight adds its catalyzing action.

The following excerpt is from a publication of the American Chemical Society entitled: "Polymerization"—

The polymerization of olefines to lubricating oils is believed to have reached the commercial stage in at least two different applications, (a) in the manufacture of an entire lubricating oil of especially high quality, (b) in the manufacture of a polymer of high molecular weight which, when blended with lubricating oil, imparts to it a high viscosity index.

The first of these developments was reported by Sullivan, Vorhees, Neeley and Shankland, of the Standard Oil Company of Indiana. This work, which included more than a hundred references to prior work, represents a thorough investigation of the effect of aluminum chloride as a polymerization catalyst at temperatures between 70° and 200°F. It was concluded that the lower the temperature of polymerization, the better the lubricating oil which was obtained as product, although slight variations in the conditions of polymerization had but little effect.

Solid hydrocarbons, generally called waxes, are found at the surface of the earth in quantities of the order of magnitude of 100–1000 parts per million by weight of earth sample. These are large compared to ethane or ethylene which are found just below the surface in quantities varying from .02 to .10 parts per million by weight. In view of the narrow melting point range, about 2°C., of the surface wax in any single area, it is probably a relatively pure substance; that is, it is composed in the main of a comparatively few compounds. Based on the assumption that the wax is formed from ethylene in the presence of chlorine and sunlight, this is not surprising. Samples obtained from widely separated areas including Texas (East, South and West), Kansas, Arkansas and California all melted within a range of 8° (62°–70°C.) and this included samples obtained on the granite in the Llano-Burnet uplift in Texas. Probably the principal factor contributing to the type of wax is the intensity and duration of sunlight.

Just below the surface of the earth, without benefit of sunshine of course, another wax is found in appreciably smaller quantities than the surface wax. Because of the lack of sunlight polymerization has not progressed so far as at the surface and consequently this wax occurs in smaller quantities and has a much lower melting point range, namely, 38°–40°C. in Refugio County, Texas.

That ethylene in the presence of chlorine will polymerize was demonstrated in the laboratory by bubbling the gas through a concentrated salt solution for two days. A very appreciable quantity of wax was formed which melted at 53°–55°C. A larger quantity was formed by passing ethylene through an aluminum chloride solution. Dallas city gas consisting principally of methane when passed through a concentrated salt solution resulted in a very negligible quantity of wax being formed. Although the gas was treated to remove unsaturated hydrocarbons, it is possible that they were not completely removed and the very small quantity of wax formed may have been due to some residual unsaturates.

The liquid hydrocarbons found immediately below the surface occur in much greater quantities than any of the other hydrocarbons. The average background values are of the order of 1000–2000 parts per million by weight. Over the edges of some fields they have been found in quantities at least as great as 10,000 parts per million by weight, or 1% which when translated into volume relations means about 2%. These concentrations, it should be noted, are of the same order of magnitude as those occurring in commercial accumulations of oil.

From the viewpoint of exploration these near-surface liquid accumulations are very valuable. In the case of gently folded structures the highest concentrations occur over the edges of the buried deposit due to the fact that the shale trapping the buried accumulation has been "clogged" by the oil formed in it at the time of formation of the accumulation. This will be discussed at greater length in connection with the method of accumulation of buried deposits. In the case of structures which have been subjected to folding subsequent to the original accumulation, especially where the folding is steep, the greatest concentration of hydrocarbons near the surface may occur over the top of the buried deposit.

In moving toward the surface the gases will carry some of the subsurface waters with them. In so doing they will also transport some of the minerals dissolved in these waters. The relative quantities of different minerals so transported will of course depend on their concentrations in the subsurface waters, also their relative densities and perhaps their molecular size, and finally on the proximity of the particular waters to the surface. In view of the fact that the water is lighter than its contained minerals, it is likely that the proportion of water transported upward will be greater than the proportion of water to minerals in the subsurface formations. The water so removed by the migrating gases will tend to be replaced by meteoric water entering the sands at the outcrops. If the water supply at the outcrops is plentiful and the permeability of the water sands is sufficiently great, the displaced connate water will be readily replaced by the entering meteoric water and eventually the subsurface waters will resemble the surface waters in character. This condition is best exemplified by the subsurface waters in the Rocky Mountain area.[1] If, however, the sand permeabilities are small, even though the water

[1] R. Claire Coffin and Ronald K. DeFord—"Waters of the Rocky Mountains." *Problems of Petroleum Geology*, pub., A.A.P.G. 1934, p. 927.

supply at the outcrops may be ample, the meteoric water will not replace the connate water as fast as the latter is removed with the result that the mineral concentration of the subsurface waters will increase. This is the case in the Appalachian area where in some cases the connate water has been completely removed and the oil has settled in the synclines.[2] Of course, there are all intermediate stages between these two extremes.

The concentration of these minerals will naturally be greatest where the leakage of gas is greatest and as a result should be of service in exploring for buried oil and gas deposits. Concentrations of these minerals near the surface of the earth are very appreciable and bear a significant relation to buried oil and gas fields.

In view of the large concentrations of liquid hydrocarbons occurring near the surface of the earth, it would seem that under slightly more propitious circumstances commercial accumulations should be rather prevalent in the subsurface formations where relatively permeable and porous formations are folded, so that accumulation may occur and its escape be prevented by a suitable seal. The chlorine content is even more abundant than near the surface. As mentioned previously, even with a large differential between the permeabilities of a sand and an overlying shale, there is surprisingly little horizontal migration of hydrocarbon gases. However, in a folded structure these gases move to the high point from all directions in the immediate vicinity of the high point. This will result in a small accumulation of the gases at the high point. As a result of the chlorine present the unsaturated hydrocarbon gases will have an opportunity to polymerize to a greater degree than otherwise. This will occur at the shale sand contact where, also, due to the larger surface area of the shale particles, a surface catalytic effect will contribute. The heavier hydrocarbons formed will tend to clog the pores of the overlying shale, thus slowing up the upward migration of the gases, and at the same time in these heavier hydrocarbons more of the gases will be dissolved. This accumulation process will soon result in the formation of some free oil, which, of course, will continue to increase in size and so an oil field may be born. Around the edges of the growing accumulations where the shale cap has not yet been clogged, the gases will escape at a greater rate than over the accumulation where the shale permeability has been reduced by the "clogging" of the hydrocarbons themselves.

[2] Paul D. Torrey—"Composition of Oil-Field Waters of the Appalachian Regions." *loc. cit.*, p. 841.

The gas arriving from below will dissolve in the oil. As the quantity going into solution will be proportional to the area or the square of the radius, whereas the leakage around the borders of the field is directly proportional to the radius of the field, more will accumulate than will leak and the accumulation will continue to grow. It is assumed in this discussion that the permeability of the shale has some intermediate value which will permit the lighter methane with smaller molecular size to escape faster than the heavier unsaturated gases.

In case the permeability of the overlying shale is appreciably less than that assumed in the above description, a gas and not an oil accumulation will result. The gases will accumulate as before with the difference that the methane will not escape much faster than the heavier unsaturated gases. As it will accumulate at least five times as fast as the unsaturated gases, the latter, being immersed in a much larger volume of the saturated and consequently stable gas, will not have a very great opportunity to polymerize and consequently no very large quantities of oil will result. Furthermore, those that do polymerize may not get further than the distillate stage of their otherwise normal life cycle.

If the permeability of the shale is greater than that which is required to form the oil accumulation of the first instance, the gases will not be sufficiently retarded to polymerize appreciably, and so there will be neither an oil or a gas field.

In this discussion the shale permeability has been considered as the principal factor. It should not be forgotten though that in addition the surface catalytic effect of the shales may be of great importance and also that there may be present in variable amounts other catalyzers such as aluminum chloride. Of course, the quantity of gases issuing from the sources (basement complex or coal deposits) in some localities may be so small that it is insufficient to form an appreciable accumulation of oil or gas.

Even though unsaturated hydrocarbon gases were not present the above mechanism of accumulation would function if the heavier saturated gases were sufficiently more reactive than methane.

This hypothesis is consonant with the carbon ratio theory of David White to a limited degree. Previous to White's pronouncement of the theory, H. D. Rogers and others had observed that the type of oil accumulation was related to the carbon ratio of coals contained in, or overlying the formation in which the oil and gas fields were located. The carbon ratio theory explains the observed facts by stat-

ing that the increased pressures and temperatures due to the deformation of the rocks, metamorphose the heavier oils into lighter ones, then into gas and finally permit the gas to escape. These forces are the same as those that increase the carbon ratio of the buried coal deposits by driving out the volatile matter. It is difficult to harmonize the two quite different results that derive from the same set of forces. The theory here proposed is that the pressure of deformation at first compacts the sediments, particularly the cap rocks, thus decreasing the permeability and as a result they trap a greater proportion of the saturated methane. This relatively inert gas being present in greater quantities will retard the polymerization of the less stable unsaturated hydrocarbons and consequently the oil will become of lighter gravity than otherwise. Further deformation may result in fissuring of the cap rock which will permit the gas to escape in preference to the oil and, consequently, the transformed light oil pool may revert to a heavier one. In this case, if the pool were originally a gas accumulation only, the fissuring might permit the gas to escape entirely. It should be borne in mind that the time of application of the forces of deformation in relation to the time of burial of the sediments is important. If those forces come into play soon after burial the permeabilities of the cap rocks may be altered sufficiently soon to result in the formation of gas fields only, in which case further deformation may result in their extinction. The maximum forces will of course occur closest to the focus of deformation. The increased pressures due to overburden will of course have the same effect in decreasing the permeabilities as the increased pressures due to deformation, and, consequently, on the average, deeper accumulations should be composed of lighter constituents. Older geologic formations at a given depth might be less permeable due to the time factor. As limey shale is likely to be less permeable than non-limey shale, the fields occurring in connection with them are apt to be more volatile, other factors being equal. As pre-Tertiary formations are in general more limey than Tertiary formations, one would expect on the average to find in them more volatile accumulations at a given depth, which seems to be the case.

It is quite certain that coal is derived from buried vegetable matter, which, upon being subjected to pressure due either to overburden or deformation, was devolatilized. Oil shales may have been derived from buried animal and vegetable matter. However, it is more likely that the concentrations of hydrocarbons occurring in oil shales result from the absorption and polymerization of hydrocarbon

gases leaking through them. Many samples of soil analyzed have been found to contain concentrations of liquid hydrocarbons approaching the order of magnitude of concentrations found in oil shales. Oil shales may be merely shales whose surface absorption and catalytic effects are large and consequently they entrain and polymerize large quantities of the hydrocarbon gases. In view of the fact that bones of animals rarely survive, it is not at all logical to expect the remaining parts to survive at all. It seems reasonable to assume that any vegetable matter that survives burial will eventually coalify as a result of devolatization by pressure.

In conclusion it would seem that so far as migration is concerned, the gases are the principal participants and also that the direction of migration is essentially vertical. The oil is formed practically in place. There are undoubtedly a few exceptions to this as when deformation subsequent to accumulation results in relatively large fissuring or faulting, oil accumulated in one porous formation may move as oil to another. Also oil or gas accumulated in a trap may as a result of regional tilting be removed from the original trap. The large time factor permits of sufficient quantities of gases to migrate through the relatively impermeable formations to account for the accumulation of commercial oil and gas fields. It is due to the presence of chlorine, and not mere coincidence that oil is almost always found in marine sediments. In fact, when found otherwise, which is only occasionally the case, it has probably been originally formed in marine sediments and has subsequently migrated as oil to its non-marine resting place. And finally, secondary leakage of gases from an existing field and the resulting gaseous, liquid and solid hydrocarbons, as well as mineral concentrations produced near the surface of the earth, are a means of finding as yet undiscovered reserves.

The above is offered as a working hypothesis with the hope that it will contribute something of value to the final solution of the important problem of the origin, migration and accumulation of oil and gas.

FIGURES

The forces acting on a bubble of gas are shown in Fig. 1. In a homogeneous isotropic sand this force is vertical as shown in the upper portion of the figure. At the interface of a sand and shale there will be a horizontal component of force, the magnitude of which will depend on the slope of this interface. For a slope of 50′ per mile, this component will be 1% of the vertical. At the apex of an anticline this force will cause gas to move from all directions in the immediate

vicinity toward the apex. The lower portion of the figure represents the force diagram in plan. It is apparent that there will be an accumulation of gas at the apex. This will give the unsaturated gases an opportunity to polymerize.

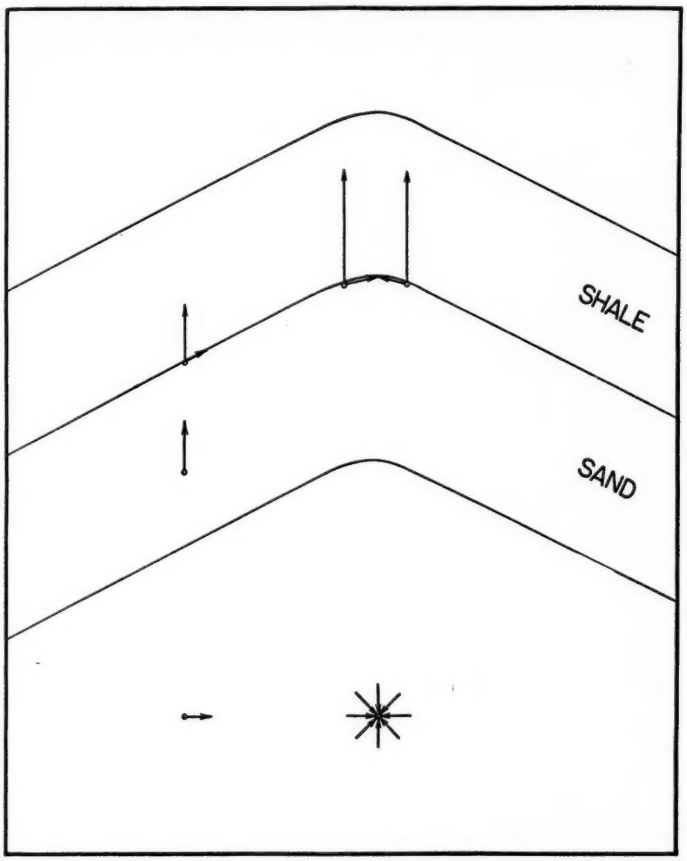


FIG. 1.

Structural formulas for some of the hydrocarbons are shown in Fig. 2. The second from the bottom in the right hand column is ethylene (C_2H_4) and ethane (C_2H_6) is shown directly opposite. It is not improbable that the direct ancestor of ethylene in the basement may be acetylene (C_2H_2), which is readily formed in the presence of water from a carbide such as calcium carbide (CaC_2). It is quite likely

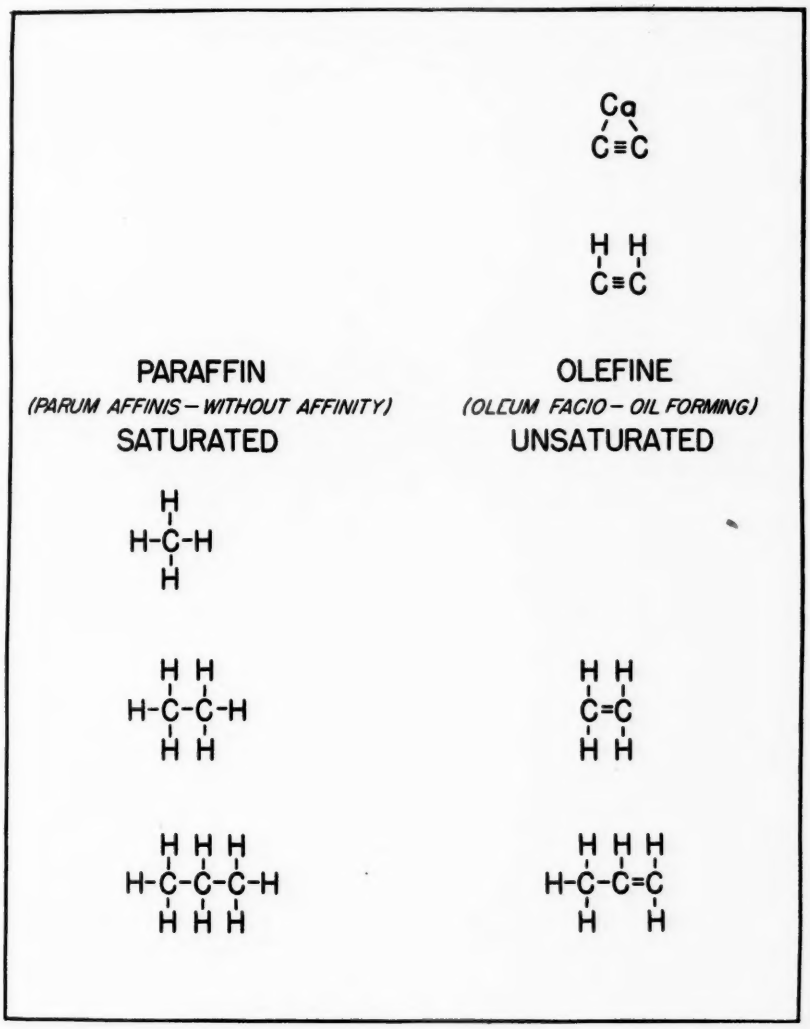
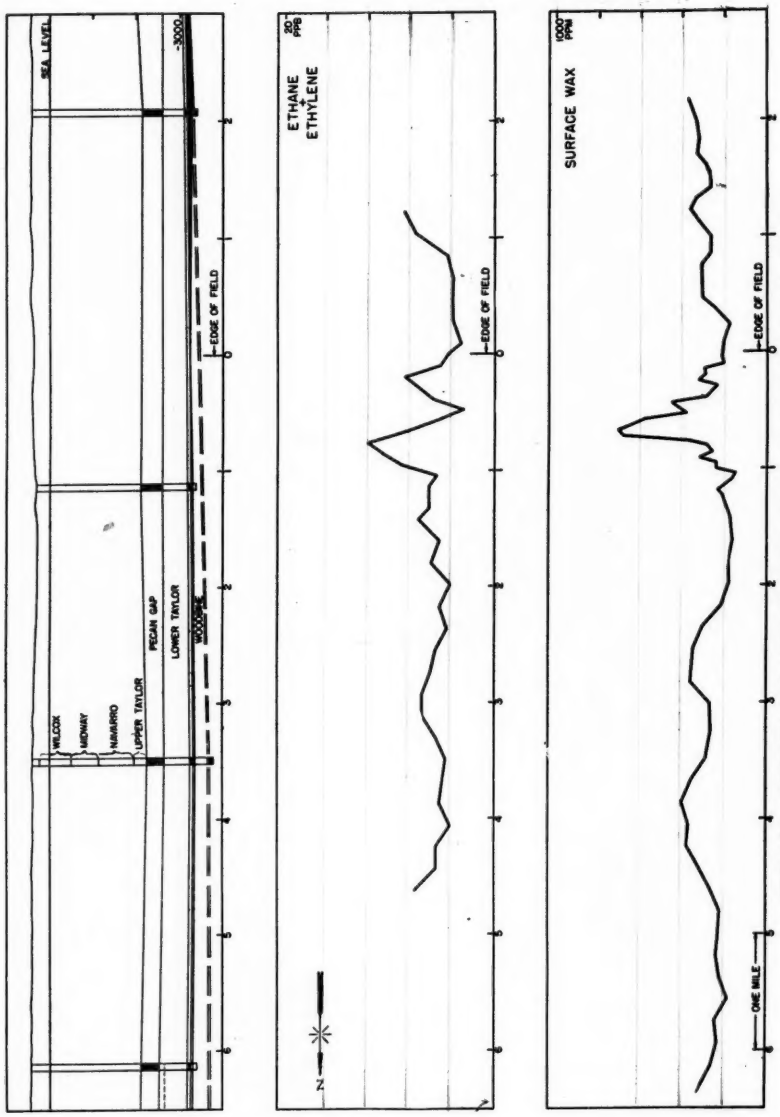
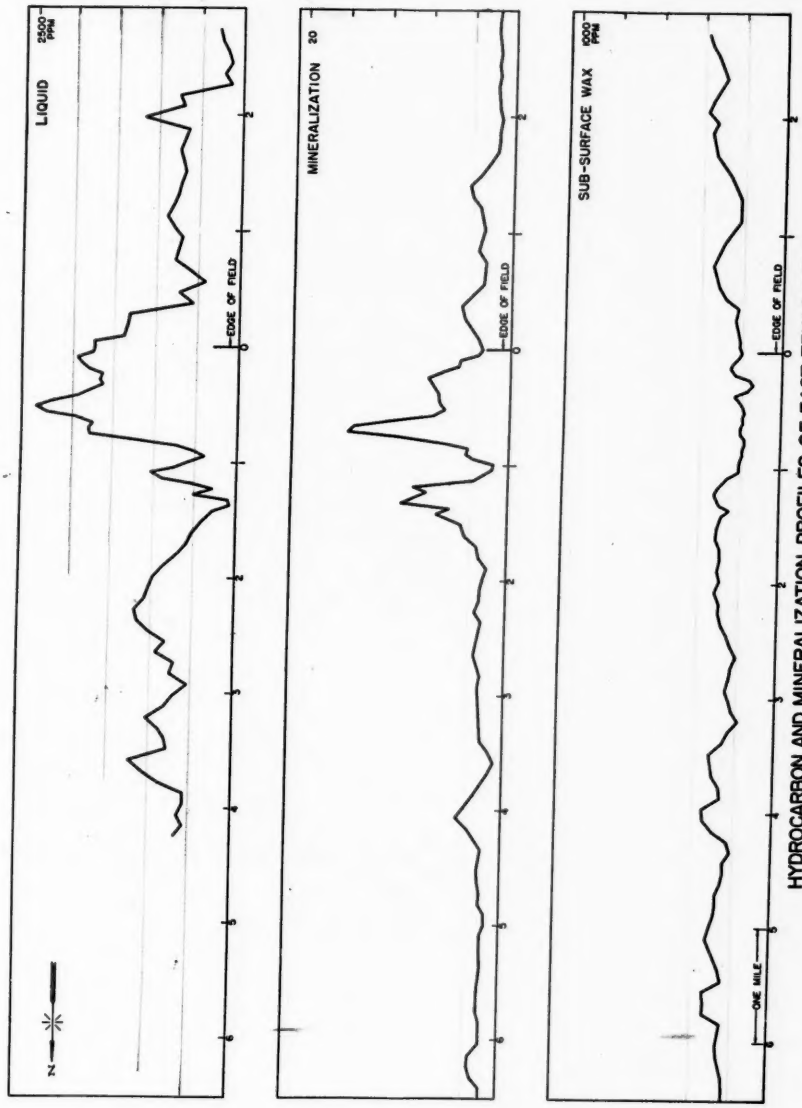

Ca
C≡C
H H
C≡C
PARAFFIN
(PARUM AFFINIS – WITHOUT AFFINITY)
SATURATED
OLEFINE
(OLEUM FACIO – OIL FORMING)
UNSATURATED
H
H-C-H
H
H H
H-C-C-H
H H
H H
C=C
H H
H H H
H-C-C-C-H
H H H
H H H
H-C-C=C
H H

FIG. 2.



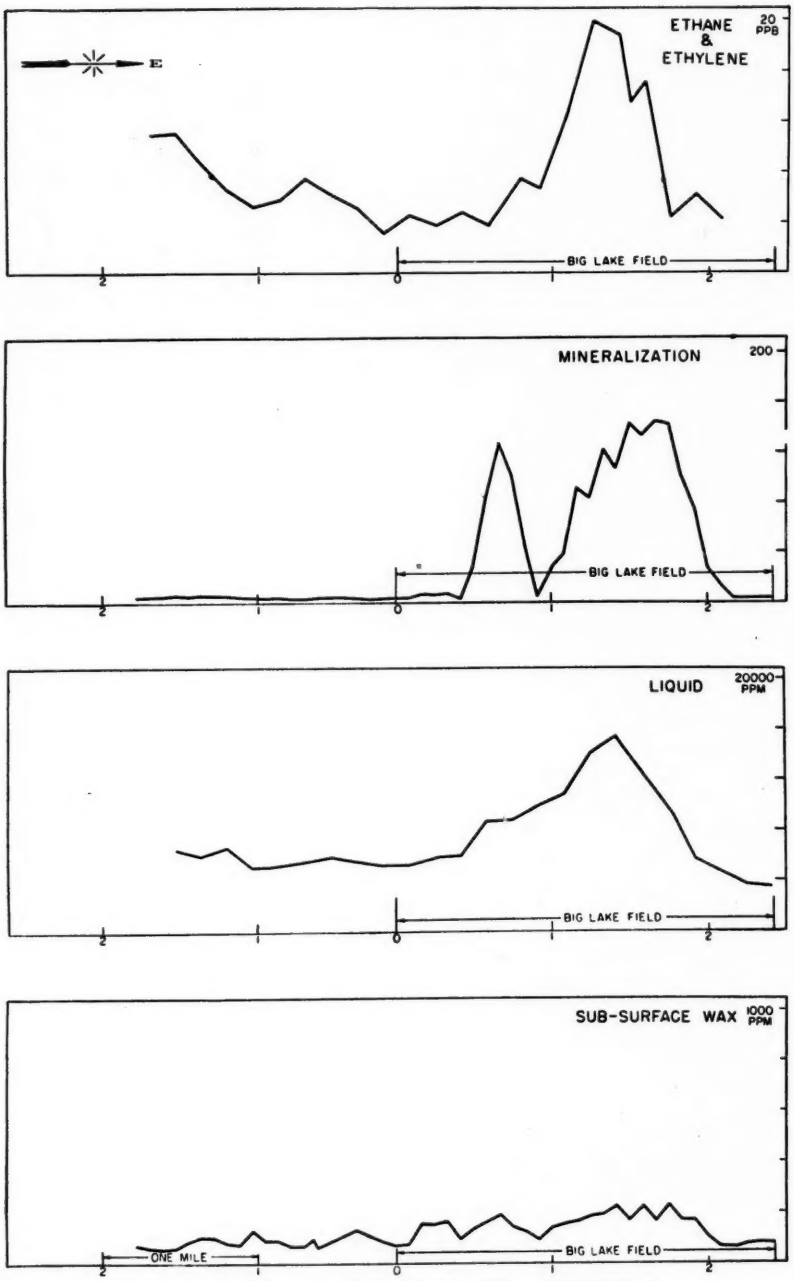
GEOLOGIC SECTION AND HYDROCARBON PROFILES OF EAST TEXAS FIELD

FIG. 3.



HYDROCARBON AND MINERALIZATION PROFILES OF EAST TEXAS FIELD

FIG. 4.



HYDROCARBON PROFILES OF BIG LAKE FIELD

FIG. 5.

that when the earth cooled, carbides were formed, as carbon and the metals were the first to condense. All the compounds in the olefine series are much more reactive than those in the paraffin series.

In Figs. 3 and 4 gaseous, liquid and solid hydrocarbons as well as mineralization profiles are shown relative to a geologic section of the north edge of the East Texas field. The profiles run North from Gladewater toward Gilmer. The highest values occur just North of the edge of the field. The subsurface wax is not significant. This is the case for all areas so far surveyed. It probably forms too slowly.

Profiles across the Big Lake field in Reagan County, Texas are shown in Fig. 5. In this case the highest values occur over the field. The surface wax values which are not shown are undoubtedly contaminated by oil waste on the surface.

ON GEOCHEMICAL PROSPECTING—I*

LEO HORVITZ**

ABSTRACT

The first type of geochemical prospecting, that of searching for and recognizing visible oil and gas seeps, is one of the oldest methods of prospecting for petroleum deposits.

A second type of geochemical prospecting, that of *soil gas analysis*, has been of record in the literature for some ten years, and depends upon the microanalysis, for hydrocarbons, of "underground" or interstitial soil air.

A third type of geochemical prospecting is described, that of *soil analysis*, which has been recently developed and depends upon the separation, identification and quantitative determination of significant constituents which are entrained, occluded and adsorbed by the soil particles. These significant constituents exhibit a wide range of molecular weights, from hydrogen through gaseous, liquid and solid hydrocarbons and their derivatives. All these constituents tend to show the same significant patterns, which in general fall into two classes, the narrow elongated pattern characteristic of faulting, and the localized "halo" pattern which tends to follow and define the edges of the underlying production. This "halo" pattern has been found over both structural and stratigraphic traps.

INTRODUCTION

Geochemical prospecting dates back to the early days of the pioneer who searched for visible gas and oil seepages as indications of petroleum at depth. That this means of exploration was successful, is proven by the fact that of one hundred and forty-one salt domes discovered prior to February, 1936, in one geological province alone, thirty-five owe their discovery to the detection of associated macroscopic gas or oil seepages.[1]

A more recent type of geochemical prospecting, which has been of record in the literature for some ten years, depends upon the detection of microscopic seepages in "underground" or interstitial soil air. This method is based on the principle that the components of an oil or gas deposit flow continuously from the reservoir, through the various overlying strata, into the atmosphere, by means of diffusion, effusion, and permeation. These phenomena are readily conceivable when we

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[1] Sawtelle, George, "Salt Dome Statistics." *Gulf Coast Oil Fields*, Publication of the American Association of Petroleum Geologists, pp. 109–118, 1936.

consider that diffusion can take place through metals,[2] fused silica,[3] various glasses,[4] and other solids normally regarded as impervious.

The writer's object is first to describe briefly the salient features of this second type of geochemical prospecting and then to discuss more fully the third and most recent type, that of *soil analysis*.

I. MICROANALYSIS OF "UNDERGROUND AIR"

In 1929, G. Laubmeyer[5] described methods for collecting samples of soil air from systematically located bore holes and analyzing these samples for traces of methane. His investigations indicated that the soil air over a producing zone is richer in methane than is the soil air over a barren area. Briefly, Laubmeyer's technique consisted in digging bore holes one to two meters deep, closing these holes with a special seal, and allowing twenty-four to forty-eight hours for the composition of the enclosed air to reach equilibrium. A sample of this air was then extracted for analysis. Laubmeyer points out that the hydrocarbon content of the soil air sample, collected in this manner, consists principally of methane, since hydrocarbons heavier than air would not tend to diffuse into the bore hole.

In 1932, Russian investigators,[6] under the leadership of V. A. Sokolov, became engaged in similar work. Their technique in collecting samples consisted in first partially reducing the pressure in the bore hole and then collecting a sample of soil air by displacement of water in a suitable container. The samples collected by the Russians were found to contain heavier hydrocarbons, as well as methane. Using liquid air, they separated the hydrocarbons into two fractions: (1) the light fraction, which is noncondensable at the temperature of liquid air and which contains the methane and ethane; (2) the heavy

[2] Ham, W. R., "Diffusion of Hydrogen through Platinum and Nickel and through Double Layers of these Metals." *J. Chem. Physics*, Vol. 1, pp. 476–481, 1933.

[3] Braaten, E. O., and Clark, G. F., "The Diffusion of Helium through Fused Silica." *J. Am. Chem. Soc.*, Vol. 57, pp. 2714–17, 1935.

[4] Urry, William D., "The Permeability of Various Glasses to Helium." *J. Am. Chem. Soc.*, Vol. 54, pp. 3887–901, 1932.

[5] (a) Laubmeyer, G., U. S. Patent No. 1,843,878, issued Feb. 2, 1932.

(b) Laubmeyer, G., "A New Geophysical Prospecting Method, Especially for Deposits of Hydrocarbons." *Petroleum*, Vol. 29, No. 18, pp. 1–4, 1933.

[6] (a) Sokolov, V. A., "Methods of Exploration for Natural Gas." Monograph, 1932. (b) Sokolov, V. A., "Summary of the Experimental Work of the Gas Survey," *Neftyanoye Khozyaystvo*, Vol. 27, No 5, pp. 28–34, 1935. (c) Sokolov, V. A., "Methods of Interpretation of the Gas Survey." *Neftyanoye Khozyaystvo*, Vol. 17, No 5, pp 18–23, 1936.

fraction which condenses and is not removable at that temperature, and which is made up of a mixture of complex hydrocarbons and their derivatives.

The results of the Russian workers corroborated Laubmeyer's conclusions in that they, too, found that maximum concentrations of hydrocarbons occur in the soil air over productive zones, with minimum values over barren areas. These investigators suggested that a high ratio of the light fraction to the heavy fraction is indicative of a gas reservoir, while a low ratio of the same two fractions is evidence for the existence of an oil deposit.

Antonov[7] shows that the depth of the oil or gas deposit may be computed, assuming normal diffusion (from a point or line source) through homogeneous media. However, he neglects to consider adsorption and absorption phenomena, lack of uniformity due to faulting and horizontal migration, factors which are essential to the practical application of depth formulae.

The limitations of the *soil gas analysis* methods are most clearly described in the following quotations from the Russian literature:

"In carrying out the gas survey in the Chusovskiye Gorodki district, great difficulties were encountered while taking the samples. The presence of a moist cohesive clay and the proximity of ground water prevented the taking of samples of soil air. During the taking of the samples, water, but no gas, was drawn from the bore hole. A total of only nine samples was successfully taken in the Chusovskiye Gorodki district, and even these were situated on the elevated bank of the Chusovaya River. Analysis of these samples showed a very low content of hydrocarbons close to the limits of error of the determination. The average content of heavy hydrocarbons in these samples was about .00015% and the content of methane was about .0003%. In this way the sampling equipment used by the gas survey parties prevented a gas survey from being carried out in the Chusovskiye Gorodki district."[8]

Mogilevskii writes:

"The primitive technical equipment of gas survey parties does not permit a gas survey to be made in places where solid rock outcrops, in alluvial gravel deposits, in sand hills (because of their inten-

[7] Antonov, P. L., "Contribution to the Theory of the Gas Survey." *Neftyanoye Khozyaystvo*, Vol. 26, No. 5, pp. 19–23, 1934.

[8] See reference 6 (b).

sive aeration) in compact clays, etc. Still greater difficulties arise in regions with a high ground-water level."[9]

II. SOIL ANALYSIS FOR ENTRAINED CONSTITUENTS

Prior to 1937, research was initiated in the Subterrex Laboratories with a new approach to geochemical prospecting in view.[10] It was thought that during the upward migration of the constituents of the oil deposit, there is present a strong tendency for their adsorption and occlusion by the soil particles. It was anticipated that analysis of the *soil itself* for these entrained constituents[11] would yield substantially greater concentrations than would result from the analysis of the interstitial air. Ensuing experiments showed this supposition to be correct. Whereas analysis of interstitial soil air resulted in finding amounts of hydrocarbons only slightly higher than the sensitivity of the most highly developed analytical techniques available, the soil analysis method raised the resolving power well above those same analytical limitations. While the *soil gas* methods depend upon a large and undetermined quantity of soil from the interstices of which the air sample is drawn, the *soil analysis* method has yielded satisfactory results with samples as small as fifty grams. Further, the new technique permits the use of completely water logged samples as well as those that are moisture free. Of paramount importance is the invaluable information obtainable during the drilling of wells, through analysis of cores and cuttings. Finally, from an exploration viewpoint, the secrecy afforded by the *soil analysis* technique is, of course, obvious.

A. SOIL ANALYSIS FOR THE VOLATILIZABLE CONSTITUENTS

Of the hydrocarbons composing petroleum, only the more volatile ones would be expected to reach the surface of the earth by upward migration from the buried deposit. Due to its greater rate of diffusion, methane should be found in relatively large amounts. However, since this compound is usually present in soils as a result of bacterial action upon vegetable and animal matter, its determination may be of no

[9] Mogilevskii, G., "The Gas Survey Deserves A Wide Use." *Neftyanoye Khozyaystvo*, Vol. 27, No. 5, pp. 35–37, 1935.

[10] Rosaire, E. E., and Horvitz, Leo, Patent Pending.

[11] The term "entrained constituents" is used to denote those constituents which are adsorbed, occluded, or otherwise closely bound to the soil, distinguishing these from constituents contained in the soil interstices, such as "underground air."

special significance insofar as exploration for petroleum or natural gas is concerned. For this reason, it was essential that an apparatus be developed by means of which a quantitative separation of methane from ethane and heavier hydrocarbons could be effected. The technique, in its present form, is based on fractional condensation methods using a specially devised trap.[12] In order that the possible presence of significant constituents, other than the paraffin hydrocarbons, would not be overlooked, the apparatus was so designed that a "complete" analysis of the volatilizable entrained constituents of the soil could be achieved.

Experiments carried out with numerous samples, collected at various depths, from several petroliferous areas, disclosed, among the compounds determined, the presence of hydrogen, methane, ethane, propane, and a group of substances having six to twelve (and sometimes more) carbon atoms, which has been termed "pseudo-hexane."

A brief description of the method of treatment and analysis of the soil may be desirable here.[13] The samples are brought to the laboratory in glass jars which are readily attached to the analytical apparatus. The pressure in the sample jar is reduced, thereby eliminating the interstitial soil air, and the entrained constituents are then liberated in gaseous form by suitable treatment. The sought gases are freed of contaminating constituents normally present in the soil (e.g., carbon dioxide, ammonia and its derivatives, acidic substances, etc.), and then separated into several fractions by employing refrigerants at appropriate temperatures. At the lowest temperature, the lightest fraction, consisting of methane and hydrogen, remains gaseous and is readily removed from the heavier components. Of these heavier components, ethane is evolved by raising the temperature of the mixture. At a still higher temperature, propane is liberated. By raising the temperature still further, another fraction is obtained, consisting possibly of butane. The fraction remaining at the highest temperature used consists of that group of heavy substances referred to as "pseudo-hexane." The exact composition of this latter group is as yet not definitely known, but it is thought to be formed as a result of oxidation and polymerization of the lighter hydrocarbons. This explanation is supported by the fact that in the range of soil sampling depths, the concentration of this fraction decreases with increasing depth, while the soil content of the other components increases with depth.

[12] Horvitz, Leo. Patent Pending.

[13] Details of the analytical method will appear in a later publication.

The quantities of the various hydrocarbon constituents heavier than methane are determined by combustion of the individual fractions with purified air. The hydrogen is burned together with the methane present, and both the carbon dioxide and water vapor produced, are measured. The water in excess of that formed by combustion of the methane is calculated as hydrogen. The results for the various constituents are expressed in parts per billion by weight, and have been found to range from zero to as high as several thousand parts, in some instances.

DISCUSSION

The results obtained by this new technique were at first very surprising, for, in contrast with the experiences reported by Laubmeyer and Sokolov in *soil gas* prospecting, who observed that maximum hydrocarbon concentrations occur in the center of the area overlying production, the writer's empirical data, from his very first experiments, indicated definitely that the richer concentrations of adsorbed hydrocarbons occur around the edges of established production in a "halo" pattern. An explanation of this phenomenon has been proposed by E. E. Rosaire.[14] He suggests that the "halo" pattern results from shallow mineralization produced by the deposition of minerals from ground waters during their upward migration. This mineralization produces a less permeable zone immediately over the structure, so that subsequent migration of hydrocarbons would result in relatively greater concentrations around the edges, rather than over the center. He substantiates his view by pointing out that drilling rates are lower for wells over structures than for those in the immediately surrounding territory. The existence of electrical and refraction anomalies over structures further supports his theory. Thus far, no examples have been observed wherein the "halo" pattern was materially violated, although one oil field in Pennsylvania, from which only a small number of samples were analyzed, may be an exception to this rule. However, this was a localized maximum and not the characteristic, broad maximum reported by Laubmeyer and the Russian investigators. It is interesting to note that, in this particular case, there was so little connate water in the sand that an artificial water drive was required to maintain production.

From experience accumulated during the past two years, several general conclusions have been drawn concerning the relative merits of

[14] Rosaire, E. E. "Shallow Stratigraphic Variations over Gulf Coast Structures." GEOPHYSICS, Vol. 3, No. 3, pp. 96–115, 1938.

the various volatilizable, entrained constituents of the soil as related to prospecting for oil and gas. Of considerable significance is the recognized fact that ethane and propane have no known natural source other than petroliferous deposits. For this reason, the greatest reliability is attached to their presence.

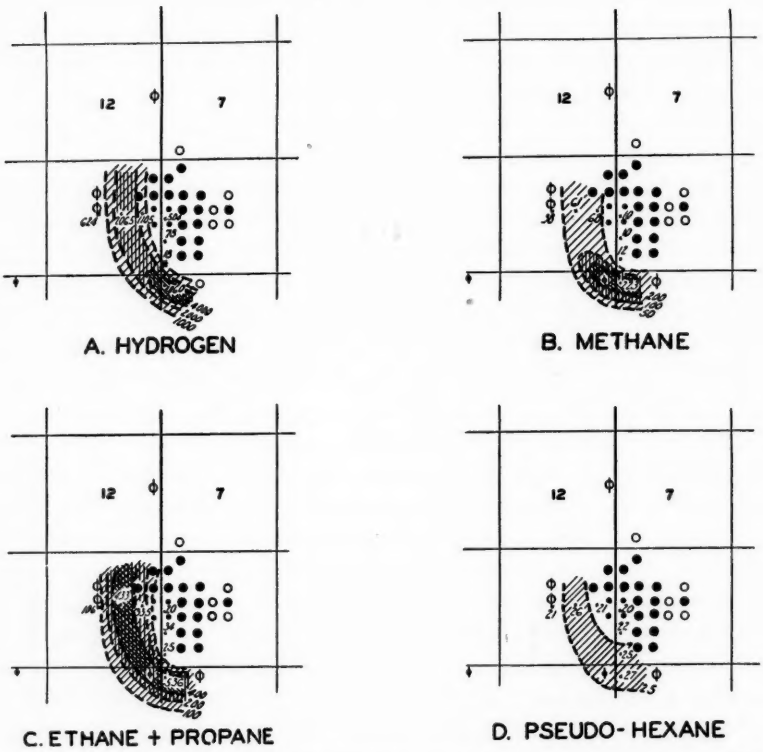

FIG. 1. Gaseous constituents by soil analysis. Small symbols indicate wells drilled before and large symbols wells completed after the soil survey.

The determination for significant methane is limited, in general, to areas void of profuse vegetation. In the arid and semi-arid regions of West Texas, satisfactory results have been obtained.

Analysis for "pseudo-hexane" is of greatest value in exploration in West Texas and other areas, where the presence of caliche makes difficult the collection of samples by hand augers, at depths of more than two to four feet. Since, at such depths (especially in dry areas), the evaporation and oxidation of ethane and propane are relatively

rapid, their content is small and often not very significant. However, "pseudo-hexane," being considerably heavier and so more readily adsorbed, tends to accumulate at these shallow depths, and its determination generally yields satisfactory results.

As yet, no great reliance has been placed on the presence of hydrogen in the soil, although it has been found in some petroliferous areas where it displayed the same geometric pattern as ethane. Of interest is the fact that it has been detected in large quantities in cores taken from a drilling well which later produced some oil.

Figure 1 shows the results of "complete" analyses of samples collected at depths of two to four feet at the Ramsey Oil Field, Payne County, Oklahoma. (A) represents the hydrogen content of the samples in parts per billion by weight, (B) the methane, (C) the ethane-propane,[15] and (D) the "pseudo-hexane."

Although but a few samples were available for analysis, it is of interest to note that the largest values for the different constituents were found in those samples located closest to the edges of the producing zone.

Outstanding are the *unusually high* values of methane, ethane-propane, and hydrogen observed. This may be explained by the fact that samples were taken when the ground was snow-covered, thus producing a seal which reduced the rate of evaporation and oxidation of these constituents. This explanation is supported by the results of a later, more detailed survey of this area, when samples collected at the same depths during the summer of 1938, were analyzed for the ethane-propane content. The more recent results substantiated the general pattern suggested by the preliminary analyses, but the values were considerably lower, being comparable with those obtained in other geological provinces. Of special significance is the fact that each of the constituents determined yielded the same general contours, suggesting that each is correlatable with petroleum at depth.

The results of a soil analysis survey of the Hastings-Friendswood area, from which samples collected at depths of ten feet were analyzed, are shown in Fig. 2. The tendency for the higher concentrations to assume the "halo" pattern is apparent. The elongated groups of relatively high values within the "halo" probably represent surface traces of faults.

In a discussion of the results obtained at the Hastings field for

[15] With the analytical technique used in obtaining the data reported in this paper, any propane present would be collected and measured together with the ethane.

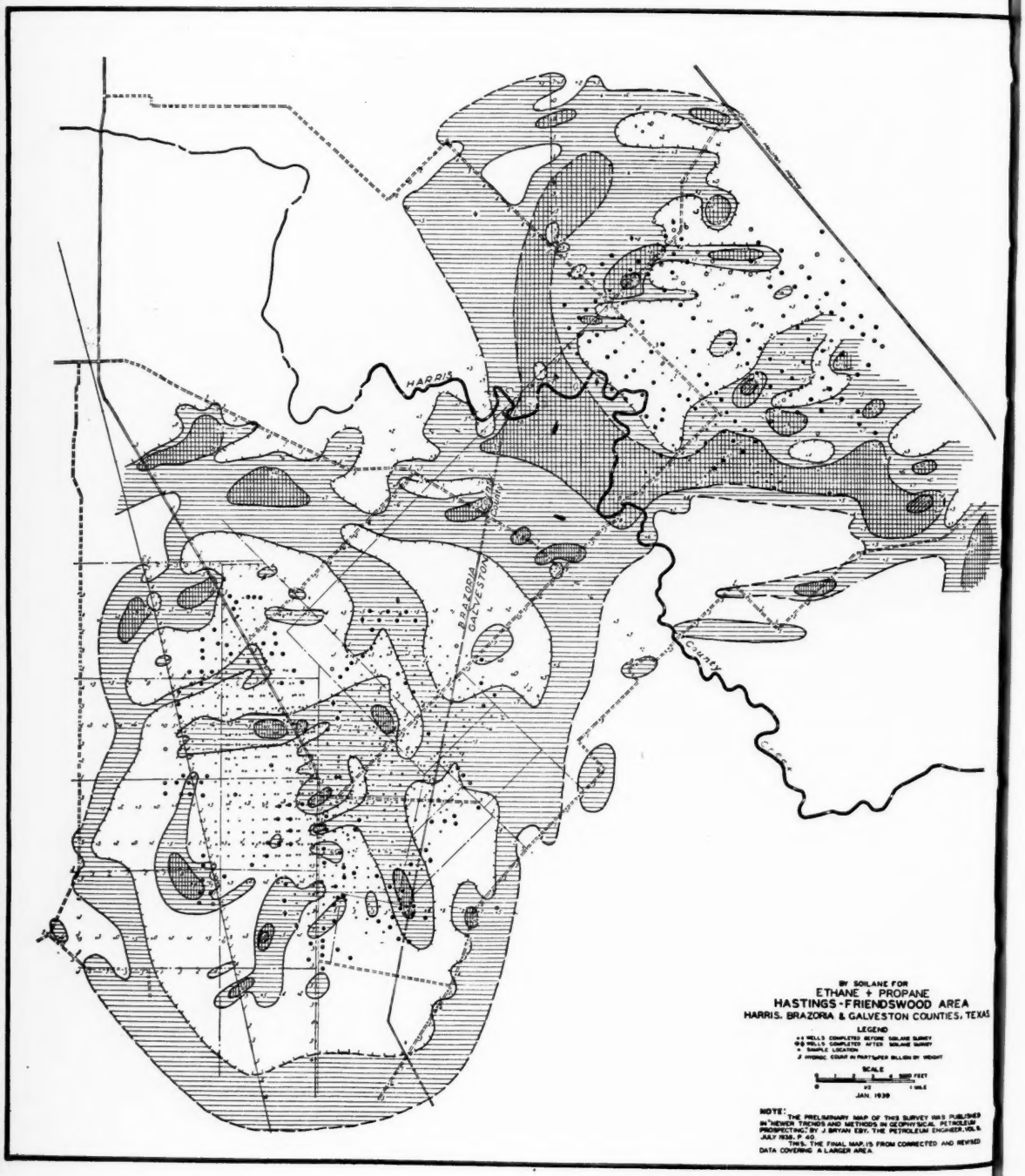
HARRIS
BRAZORIA
GALVESTON
County
BY SOHLANE FOR
ETHANE + PROPANE
HASTINGS - FRIENDSWOOD AREA
HARRIS, BRAZORIA & GALVESTON COUNTIES, TEXAS
LEGEND
SCALE
JAN. 1939
NOTE: THE PRELIMINARY MAP OF THIS SURVEY WAS PUBLISHED IN "NEWER TRENDS AND METHODS IN GEOPHYSICAL PETROLEUM PROSPECTING" BY J BRYAN EBY, THE PETROLEUM ENGINEER, VOL 9 JULY 1938, P 40.
THIS, THE FINAL MAP, IS FROM CORRECTED AND REVISED DATA COVERING A LARGER AREA.

FIG. 2

two separate determinations, carried out about six months apart, and when appreciable development had taken place in the interim, E. E. Rosaire[16] points out that in the more recent determination the high ethane-propane values tended to correspond with production, in contrast to the earlier survey in which the maximum hydrocarbon concentrations were found around the edges of the (later) productive area. As a result of our later work in this area, and in other similar

FIG. 3. Soil analysis for ethane and propane. Small symbols indicate wells drilled before and large symbols wells completed after the soil survey. Station interval is 500 feet.

areas, that conclusion is open to question, for well developed and apparently significant "halos" have been observed over areas where production had been established prior to the soil sampling.

The application of soil analysis to stratigraphic prospecting is exhibited in Fig. 3, which shows the ethane-propane values obtained by analysis of subsurface samples collected over a sand lens structure located in South Texas. Production is from the Miranda sand at an average depth of 1500 feet. Of unusual interest is the fact that in this case, also, the producing area is limited to that zone of low ethane-propane values which is bordered by the higher concentra-

[16] *loc. cit.*

tions.[17] It can be readily seen that the wells, drilled after the soil analysis survey was completed, confirmed the prediction of a considerable extension to this field.

In Fig. 4 are plotted the "pseudo-hexane" values obtained by analysis of samples taken at eight feet along a profile crossing a recently discovered field in Jefferson Davis Parish, Louisiana. It is seen that these constituents show the same distribution pattern in the soil as ethane-propane.

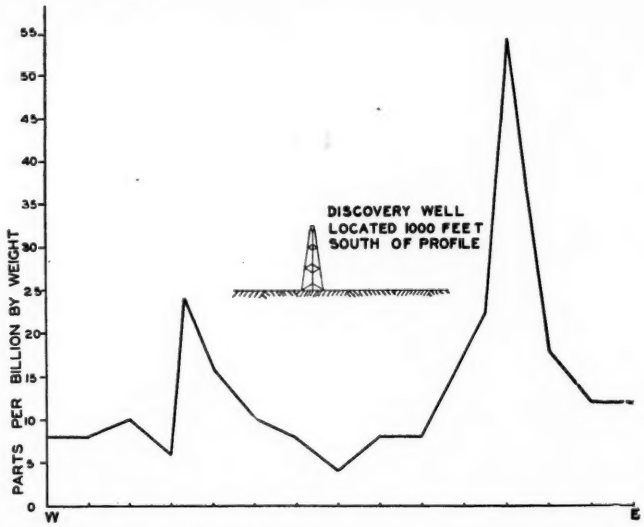

FIG. 4. Soil analysis for pseudo-hexane. Samples analyzed December 1937, producing well completed February 1938. Station interval 1,000 feet indicated along horizontal axis.

The application of the technique to core analysis is shown in Fig. 5, in which the analytical results (plotted logarithmically) are compared with an electrical log of a well that produced some oil from the sand at 7100 feet. Of the constituents determined, only the values for the hydrocarbons heavier than methane are included.

Attention is called to the important fact that the concentrations of the hydrocarbons tend to increase with depth, suggesting strongly the theory of migration of the hydrocarbons from the accumulated oil mass toward the surface. This increase, however, is irregular, apparently depending to a large extent on the porosities and permeabili-

[17] This is contrary to the report of M. G. Hoffman, *Oil and Gas Journal*, Vol. 37, No. 44, p. 24, 1939.

ties of the various strata. The results suggest that depth computations arrived at on the basis of the simple diffusion laws may lead to erroneous conclusions.

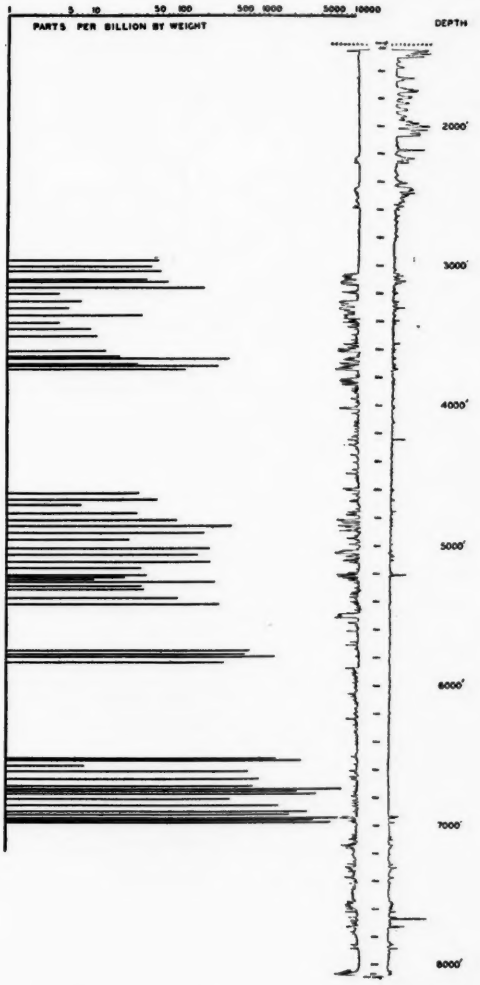

FIG. 5. Analysis of cores for hydrocarbons heavier than methane. (March 1937.)

B. SOIL ANALYSIS FOR SIGNIFICANT LIQUID AND SOLID CONSTITUENTS

The presence, in subsurface soils, of complex volatile hydrocarbons, referred to previously as "pseudo-hexane," suggested the

search for substances which might have been oxidized and polymerized to a more advanced degree. These products would be expected to accumulate at the immediate surface of the earth, where oxygen (from the atmosphere and surface waters) is available and where the conversion of the lighter hydrocarbons would be hastened by photochemical action.

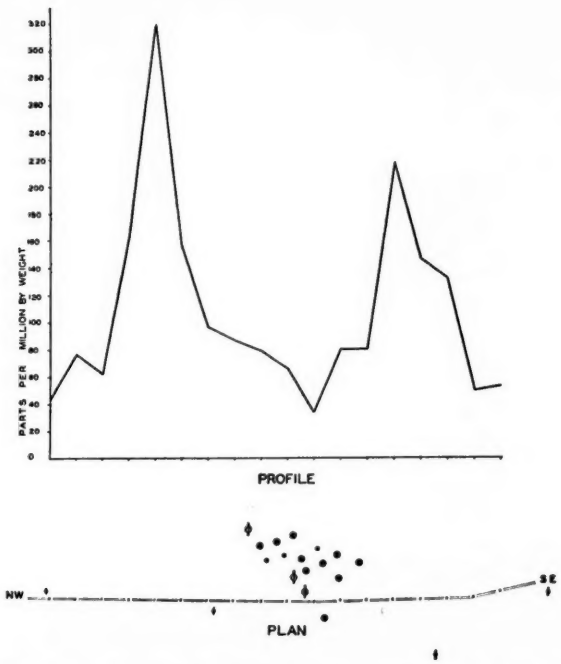

FIG. 6. Soil analysis for wax. Station interval 1,000 feet indicated along profile. Small symbols indicate wells drilled before and large symbols wells completed after the soil survey.

Based on this line of reasoning, experiments were conducted to determine if such heavy substances could be found. According to expectations, mixtures of liquid and solid materials[18] were found not only to be present, but to exist in greatest concentrations in the

[18] (a) The chemical composition of these substances will be reported in a later publication. (b) It is suggested that "pseudo-hexane" and the heavy liquid components are intermediate products formed in the conversion of the lighter hydrocarbons to the solid end-product. (c) Of interest is the fact that in the range of soil sampling depths, the ratio of the solid fraction to that of the liquid decreases with increasing depth.

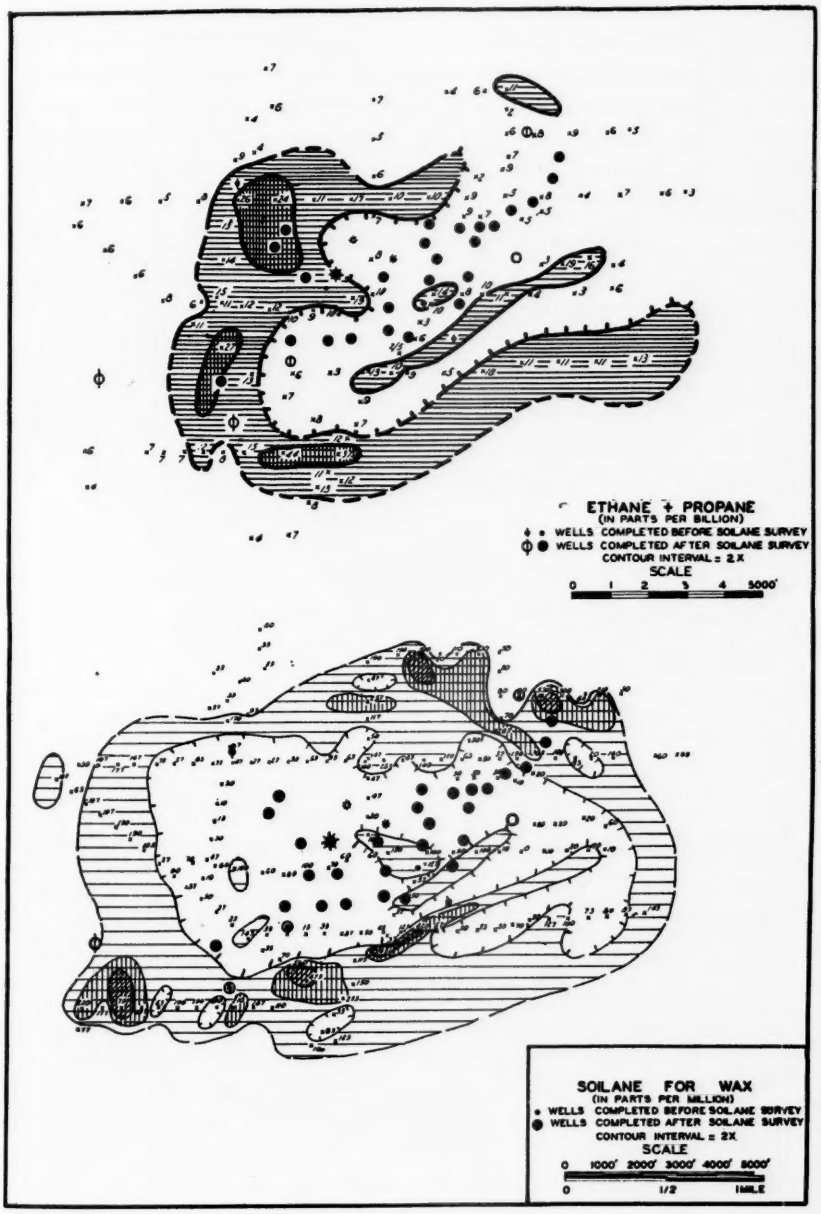
ETHANE + PROPANE
(IN PARTS PER BILLION)
WELLS COMPLETED BEFORE SOILANE SURVEY
WELLS COMPLETED AFTER SOILANE SURVEY
CONTOUR INTERVAL = 2X
SCALE
0 1 2 3 4 5000'
SOILANE FOR WAX
(IN PARTS PER MILLION)
WELLS COMPLETED BEFORE SOILANE SURVEY
WELLS COMPLETED AFTER SOILANE SURVEY
CONTOUR INTERVAL = 2X
SCALE
0 1000' 2000' 3000' 4000' 5000'
0 1/2 1MILE

FIG. 7a

shallow surface soils immediately surrounding producing structures, agreeing closely with the results of the analyses of subsurface soils for the lighter hydrocarbons. The content of these heavy products is from one thousand to ten thousand times as great as that of the lighter constituents, thus simplifying the analytical technique required for their determination.[19] Since the appearance of the mixture of these heavy substances is that of a wax, it has been termed "soil-wax."

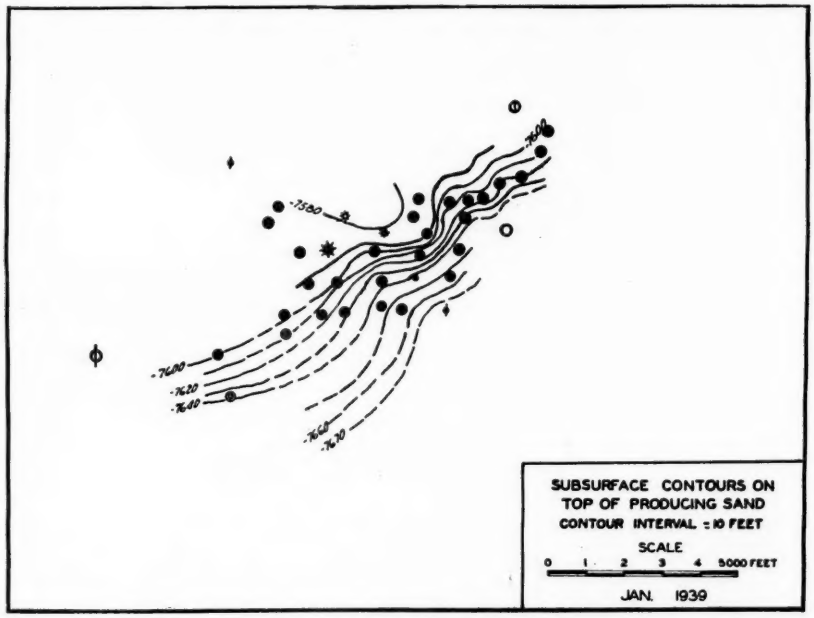

FIG. 7b

While the advantages of the "soil-wax" method in prospecting are great, in view of the ease of collecting samples and the rapidity with which the analytical work can be effected, its highest degree of accuracy is at present limited to areas which have not been recently disturbed, as by cultivation, erosion, and intensive wind action.

Figure 6 shows the results obtained with samples collected at depths of one-half inch along a profile crossing a producing field in South Texas. It will be noted that the east and west edges of production are flanked by the largest values, substantiating the "halo" pattern.

[19] Detailed descriptions of the methods used in determining these and other significant constituents will appear in a future publication.

A comparison of the results of "soil-wax" and ethane-propane surveys of a Harris County oil field is shown, together with the subsurface data, in Fig. 7.

CONCLUSIONS

The results described in this paper indicate that *soil analysis*, in its present stage of development, is a valuable aid in prospecting for petroleum deposits. Research is at present being directed towards improving the methods for extracting and determining the various constituents of the soil, and the development of more rapid methods of analysis. Studies concerning the specific adsorptive properties of various types of soils are being initiated with the hope that such information will increase the accuracy of the methods.

Experiments are also being carried on to determine the rate of formation, the origin, and the method of formation of the various constituents of "soil-wax," a most interesting and empirically significant material.

ACKNOWLEDGMENT

The writer wishes to express his appreciation to Dr. E. E. Rosaire, organizer of Subterrex, for permission to publish this paper.

DISCUSSION

Geochemical methods of the type described by Mr. Horvitz, if capable of successful application, would indeed be of extreme value to the petroleum industry. From the theoretical aspect there is much basis for hope that some such process may be developed. The experimental results of various investigators in this field, however, have thus far failed to do more than merely lend some slight support to this hope, and the published literature on the subject does not, as yet, inspire great confidence in the method.

Russian research workers have been engaged in geochemical explorations for almost ten years, but have not yet reported any discovery of petroleum by this means. According to the publications, however, they have found that over several known petroleum deposits the distribution of hydrocarbons in the near surface soils was in fair agreement with that which might be expected if the gaseous constituents were emanating from the buried reservoir through homogeneous sediments. It is remarkable that such agreement should have been found in view of certain disturbing factors, which Mr. Horvitz recognizes, such as the known lack of homogeneity in subsurface strata, the variations in adsorptive properties of the soils, and the movement of underground waters. It is difficult to ascertain to what extent the results have been influenced by contamination of the soils by producing wells.

The "halo" theory described in the paper under discussion is in direct contradiction with the findings of the Russian workers, who have accumulated much more information on this problem than has been reported in this country. Their investigations have always indicated that the higher hydrocarbon concentrations overly the

petroliferous deposits rather than surround them. True, they have measured the free gas instead of that adsorbed on the soil, but it is difficult to see any reason why the relative distributions of the two forms of hydrocarbons should not be of corresponding type.

The present writer, himself, has been collaborating in an investigation of this problem for a number of years and has conducted almost two thousand analyses, both for free and adsorbed gaseous hydrocarbons in soils without being able to establish any satisfactory correlation between the distribution of these constituents and the known petroleum deposits.

In Fig. 1 of Mr. Horvitz's paper, data are shown which are intended to substantiate the "halo" theory of hydrocarbon seepage. Only seven samples were taken, however, and this number is certainly too small to warrant the drawing of any broad conclusions concerning the method. The most complete ethane data of the paper are shown in Fig. 2, yet these data are susceptible to a number of interpretations other than that presented by the author. Moreover, there is a considerable variation between this interpretation and that made from the preliminary survey described in The Petroleum Engineer of July 1938. It is stated that the final map is based on corrected and revised data. Critical comparison of the two maps shows no orderly relation between the original ethane values and those finally obtained for the identical stations. Values which were the same in the preliminary survey have become widely different when revised and corrected. One wonders whether such changes result from inability to check the data, errors in calculations, or from a combination of such factors. Because of these apparent discrepancies it would be of considerable interest to know the actual basis for the correction and revision of the data.

Although this article presents two instances of remarkable correlation between surface wax concentration and underground petroleum deposits, no satisfactory explanation for such results has been given. The lower members of the paraffin hydrocarbon series are extremely unreactive at ordinary temperatures, even in the presence of catalysts. Of course in extended periods of time it is conceivable that oxidation and polymerization reactions might take place to some degree. However, if much time is a requirement it would seem that little significance could be attached to wax values, since the environment from which the samples are obtained is very unstable. It is well known that at shallow depths the soil atmosphere is markedly influenced by changes in atmospheric temperature and pressure, by rainfall, and by the movements of underground waters. Also, before placing too much reliance in wax concentrations, it should be remembered that waxy hydrocarbons have been found to be normal constituents of certain plants and are present in some soils as a result of the decomposition of such plants.

In view of the meagerness of the evidence disclosed and because of the conflicting results of the different investigators, it appears that Mr. Horvitz is somewhat optimistic in concluding that, "soil analysis, in its present stage of development, is a valuable aid in prospecting for petroleum deposits." It is to be hoped, for the sake of more thorough utilization of our natural resources, that some form of geochemical process may eventually prove useful, but at the present time the value of soil analysis as a prospecting method remains to be demonstrated.

A. J. TEPLITZ*

* Gulf Research & Development Co.

AUTHOR'S REPLY

The author is not surprised at the attitude of Mr. Teplitz toward the value of soil analysis in exploration for petroleum. The introduction of new processes and methods has always met with and been required to overcome the stern opposition of skeptics before success was ultimately attained. No one, the author least of all, is so optimistic that he expects the soil anlaysis method of prospecting to arise unscathed by criticism, but it is expected that opposition will be overcome. Relative to the present criticism, the points raised by Mr. Teplitz will be discussed.

The first point refers to the contradictory nature of the results reported in the present paper as compared to those of the Russian investigators. The discovery of the fact that, in general, higher concentrations of hydrocarbons are present in the soil surrounding a producing structure rather than immediately over it, was as much a surprise to the author as it is to many others who feel that on the basis of theoretical considerations alone, the "halo" pattern is not the one to be expected. It was after the analysis of but several hundred samples that the author first recognized the "halo" pattern. Now, after more than fifty thousand additional samples, collected from a large number of oil producing areas, have been analyzed, and the data found to substantiate this observation, the writer and his associates are fully convinced that the most common pattern of hydrocarbon distribution *is* the "halo." It may be well to point out here that there was an apparent exception noted in the paper. However, additional data, together with corrections in producing well locations, now shows this example also to conform to the "halo" pattern.

The next point raised refers to Fig. 1, which shows analytical data obtained from seven samples taken at the Ramsey oil field. The object in publishing this data was to show that, in some instances, methane is significant, rather than to validate the entire method. The recognition of this significance is obviously justifiable on the basis of the agreement of the methane with the ethane-propane values, even though based on the analyses of only a few samples. Also, the presence of hydrogen and "pseudo-hexane" is shown to bear a relationship to petroleum at depth. That the pattern is in conformity with the "halo" theory is evident.

Referring to Fig. 2, the author wishes to state that the map published in *The Petroleum Engineer* covers only the Hastings area, while Fig. 2 includes additional analytical data obtained from samples collected at the Friendswood oil field. Since publication of the preliminary map, the method of computation was modified to include factors which were not considered up to that time. Obviously, any method is subject to improvement as experience is acquired.

The last point raised by Mr. Teplitz is in connection with the soil-wax. He agrees that the results shown are correlatable with petroleum at depth, yet implies that, because no rigorous explanation of the formation of this material is as yet known, it should not be relied upon. By similar reasoning it would be assumed that, since the origin of oil is unknown, he would use only synthetic fuels. The paper clearly admitted the limitations of the use of soil-wax, but equally clearly established some measure of its value.

The author hopes that the following restatement of his ideas concerning geochemical prospecting will clear up much of the confusion and misunderstanding, which may at present exist.

The constituents of the soil which may play some part in geochemical prospecting

may be separated into three groups. The first group consists of the entrained gaseous constituents of the soil, the second, of the liquid and solid organic constituents, and the third, the inorganic solid constituents of the soil. The last group, of course, when useful, is limited to structural prospecting, while the first two groups may be direct indicators of petroleum at depth. The first group is the most important, for herein is found the sub-group of saturated hydrocarbons, ethane, propane, and perhaps higher paraffins which are unquestioned constituents of crude petroleum. So far as is now known, these hydrocarbons are present in shallow soils only through seepage from petroleum at depth. Using this premise as a foundation for geochemical prospecting, we may justifiably state that the remaining constituents of the first group and all those of the second and third groups are significant *only* when they yield patterns that generally conform with those obtained from ethane and propane.

The writer and his associates are now engaged in a thorough investigation of the various classes of soil constituents with special reference to geochemical prospecting, and expect to report the results of these investigations in forthcoming publications.

LEO HORVITZ

DISCUSSION AND COMMUNICATIONS

Your attention is called to this department of the JOURNAL which it is hoped may be made a regular part of each issue. It is your department, and its continuance is dependent upon your contributions.

Members of the Society frequently remark about the lack of adequate discussion of papers. Because of insufficient time, it is not always possible to obtain written discussions prior to publication but the Editor has always invited such discussion following the appearance of papers in the JOURNAL. All comments submitted which are of sufficient general interest and pertain to technical aspects of the papers will be published in this department, and such discussion will remain open until, in the opinion of the Editor, further comment is unwarranted.

Under "Communications" will be published informal letters to the Editor per taining to technical questions or other items of interest to the membership. It is hoped that, in this manner, a medium will be provided for presentation of problems or discussions which are not broad enough in scope or are insufficiently developed to justify a lengthy formal paper and yet are of sufficient importance and general interest to be worthy of publication. It is hoped that the membership and others will make use of this department, for in this manner may be brought to light interesting problems which have already been sufficiently studied by certain individuals or organizations to warrant presentation of results in the form of brief notes, or even formal papers.

It is the Editor's opinion that the art of Geophysical Exploration has reached the stage where open discussion of problems and technique is not only warranted but urgently needed if material advancement beyond our present stage is to be accomplished. As has been proven in all other technical fields, a point is reached beyond which the progress of any individual or organization is largely dependent upon the progress of the field as a whole, and such progress is predicated upon a proper dissemination of technical information. It may be argued that the geophysical field is too competitive to permit such action, but this viewpoint is gradually disappearing. The justification for this more liberal attitude becomes apparent upon reviewing the situation prevalent in other technical fields. Considering for example the highly competitive communications and related arts, it cannot be denied that the unprecedented rapidity of advance is in no small measure due to the open discussion of technical problems by the engineers and research workers upon whom rests the responsibility for advancement. A similar viewpoint on the part of Exploration Geophysicists should be encouraged, for it can only lead to a healthy stimulation of effort toward improvement and assure the unabated application of geophysical methods in future explorations. And the need for improved technique will be evident to anyone who takes the time to look beyond his immediate problems and observe the proximity of his present horizon.

EDITOR

"GROUND ROLL"

For some years organizations in this country and in Germany have been attempting to measure the free periods of vibration of geologic structures. The theory is that most localities have free periods of their own and that engineering structures which have free periods close to that of the region in which they are built will be more likely to be damaged during earthquakes than structures with free periods quite different. Measure-

ments have been made with seismographs set up near explosions and efforts have been made to find on the records predominate periods. More work has been done with shaking machines. The machines are essentially wheels with masses off center, the speed of rotation of which may be varied. They are set up with a seismograph near by and the speed of the rotor is varied. If the geologic structure on which the instrument is placed has a free period, the vibrations recorded on the seismograph should reach a maximum when the period of vibration of the rotor is in resonance with the ground. In actual practice it appears that the ground in some localities may have a number of free periods—so many as to arouse doubt in my mind as to their practical significance.

It has appeared to me that if free periods of localities are important, it should have become evident to seismic surveyors long ago. I have discussed the matter with two men working in that field and both have told me that in certain regions in Texas where there are limestones underlaid by shale the limestone apparently does take up a sort of plate vibration so that when prospectors set up on it they get nothing but a tremendous ground roll. It has appeared to me that if we wish to find out the significance of free periods of geologic structures, we should begin in some region where the structure is relatively simple and where we can seek quantitative relations. I should like to know more of the experience of seismic prospectors in regions such as that mentioned above. Many problems might be investigated. Among them are the questions of the number of free periods observed in a given region, the relation to the thickness of the limestone, how they vary as the thickness of the limestone varies. I wish that some of the men engaged in seismic exploration would interest themselves in this problem.

Yours sincerely,

(signed) PERRY BYERLY

UNIVERSITY OF CALIFORNIA
Seismographic Station
Department of Geological Sciences
Berkeley, California

April 17, 1939

PERSONAL ITEMS

(With this issue of GEOPHYSICS, the Business Manager attempts to carry on the column of personal interest to geophysicists started by M. M. Slotnick in the first issue of the Society Journal which he edited. Members wishing changes of address and items of general interest published or desiring misstatements corrected are requested to communicate with J. F. Gallie, P. O. Box 777, Austin, Texas.)

The Mid-Year Meeting of the Society of Exploration Geophysicists will be held in Houston, Texas. The exact date is dependent upon the calendar arrangements of the International Geophysical Union, members of which will make a field trip south to attend the two-day session. A general review of exploration methods and applications is scheduled for the first day of the Meeting, while the second day will be given over to technical papers and field trips. Members wishing to present papers are requested to communicate promptly with E. E. Rosaire, Chairman of the Program Committee for the Fall Meeting, 321 Esperson Building, Houston, Texas. Notices bearing the exact dates for the Mid-Year Meeting will be mailed out in ample time to permit members to make arrangements to attend.

The Independent Exploration Company announces the opening of a new office at 2015 Fort Worth National Bank Building, Fort Worth, Texas. John H. Wilson will be in charge of seismograph surveys in that region.

T. C. Richards has been transferred from Karachi, India, and may be addressed care of the Burmah Oil Company, Limited, Rangoon, Burmah.

W. A. Meszaros of the Gulf Research and Development Company has left Enid, Oklahoma, and may now be addressed at P. O. Box 177, Alva, Oklahoma.

H. C. Becker has left the Seismograph Service Corporation to enter the employ of the Barnsdall Oil Company, 2212 Esperson Building, Houston, Texas.

Curtis H. Johnson, formerly of the Rieber Laboratories, is now associated with the General Petroleum Corporation. However, he may still be addressed at 1136 Franklin Street, Santa Monica, California.

Harry A. Gibbon, whose former address was 256 Humble Building, Houston, Texas, may now be addressed at 26 Broadway, New York, N Y.

Edward L. Deloach has been transferred from the Midland office of the Atlantic Refining Company to 1742 Milam Building, San Antonia, Texas.

H. Rutherford has left Greenville, Illinois, to move to Houston, Texas. He may be addressed at P. O. Box 1023 in that city.

H. J. McCready, formerly employed by Seismic Explorations, Incorporated, is now a gravity-meter operator with the Mott-Smith Corporation. He may be addressed care of the Socony-Vacuum Oil Company, Aguas Claras, Puerto Wilches, Santander, Columbia.

V. E. Child of the Texas Company, formerly located at 929 South Broadway, Los Angeles, California, may now be reached at Box 471, Morgan City, Louisiana.

J. M. Lohse may now be addressed at P. O. Box 506, Portales, New Mexico.

It is with sincere regret that we announce the death of Dr. Donald C. Barton at Houston, July 8th. Dr. Barton was one of the organizers and earnest supporters of our Society and served as President through the term 1931–1932, during which time the Society became affiliated with the American Association of Petroleum Geologists. He was also Past President of the A.A.P.G. At the time of his death he was director of the Geological Research Department of the Humble Oil & Refining Company.

THE SOCIETY ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the Secretary within thirty days. (Names of sponsors are placed beneath the name of each nominee.)

ACTIVE

Robert Newton Bills
L. Y. Faust, W. T. Born, Andrew Gilmour

Harry Berkeley Ericson
Robert L. Kidd, Arthur E. Dietert, August F. Beck

Louis Wright Gardner
E. A. Eckhardt, G. B. Lamb, Leo J. Peters

James Edward Hawkins
C. A. Heiland, Dart Wantland, L. I. Freeman

Malvin Gerald Hoffman
R. A. LeMay, Joseph A. Sharpe, Daniel Silverman

Albert Leo Ladner
L. A. Scholl, Jr., George D. Mitchell, Jr., Alexander Wolf

Ralph D. Lynn
L. W. Konz, Norman Ricker, Robert S. Dahlberg, Jr.

Edward Dale Lynton
B. Gutenberg, Joshua L. Soske, Walter A. English

Joseph Murray Maxwell
Ralph F. Acker, Robert E. Woods, Nevin R. Shade

Arthur Behrend Nomann
Walter A. English, Hugo Benioff, Beno Gutenberg

Warner Carl Northcutt
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TRANSFER TO ACTIVE MEMBERSHIP

The Executive Committee has, in accordance with Executive Order Number C–5, advanced the following from associate to active membership:

Robert H. Mansfield
K. M. Lawrence

NOTICE OF ADDRESS OF BUSINESS MANAGER

Society Headquarters have been established in Austin, Texas, with the postal address:

J. E. Gallie, Business Manager,
Society of Exploration Geophysicists,
P. O. Box 777,
Austin, Texas

All letters pertinent to Society business, other than purely editorial matters, should be mailed to the above address. As heretofore, editorial matters should be addressed to the Editor.